

EXPERIMENTAL LIMITS ON NEW PHYSICS FROM CHARM DECAY

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Recent measurements in the charm sector are reviewed, concentrating on results which are sensitive to New Physics effects. The scope of the presentation includes $D^0 - \bar{D}^0$ mixing searches, a CPT / Lorentz invariance study, and a range of searches for rare and forbidden decays. Results from the BaBar, Belle, CDF, CLEO, and FOCUS collaborations are presented, including an important first observation.

1. Introduction

Presentations on “New Physics” can produce a feeling of anti-climax, for surely if there were any New Physics signals to report, the news would have leaked out. One does not expect to hear anything new. This talk does contain at least one first observation, however, and I’ll try to maintain some suspense by not mentioning in advance what it is.

1.1. *What I’m Not Talking About*

Today we are at a particular disadvantage because the year’s biggest charm news is outside the scope of the talk. BaBar’s discovery¹ of a narrow resonance decaying to $D_s\pi^0$ came as a complete surprise—apart from the familiar D_s^* , no mesons decaying to this final state were foreseen—and led to a flurry of speculation that the new $D_{sJ}(2317)$ might be an exotic meson. The honors were shared among the B -factories in an amusing way: CLEO announced the discovery² of a second state, the $D_{sJ}(2457)$, decaying to $D_s^*\pi^0$; and Belle, as well as confirming these results,³ made the first observation of both states in B meson decays.⁴ The decay modes and widths of the new D_{sJ} are consistent^a with these states being the $J^P = 0^+$ ($D_{sJ}(2317)$) and $J^P = 1^+$ ($D_{sJ}(2457)$) members of the $c\bar{s}$ system (with $L = 1$, and “light quark angular momentum” $j_q = \frac{1}{2}$), but their masses are a complete mystery. We thought we understood the $c\bar{q}$ mesons . . . but it appears that we don’t. This topic will be covered further in Jussara de Miranda’s talk on Standard Model charm studies.⁵

^aIn the case of the $D_{sJ}(2457)$, the Belle $D_s\gamma$ results^{4,3} rule out $J = 0, 2$, and are consistent with $J = 1$. Note that an important “exotic” hypothesis—that the $D_{sJ}(2317)$ is wholly or partly a DK bound state, and the $D_{sJ}(2457)$ likewise a D^*K state—is also consistent with the 0^+ and 1^+ assignments.

The largest discrepancy between theory and experiment in the charm sector is also off-limits, as no one imagines that new physics is responsible. But we still don’t understand why the measured cross-section^{6,7} for $e^+e^- \rightarrow \psi\eta_c$ is an order of magnitude larger than the NRQCD prediction; the ingenious suggestion⁸ of $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow \psi\psi$ contamination has now been ruled out.⁹ The $\psi c\bar{c}$ fraction in $e^+e^- \rightarrow \psi X$ is likewise far “too large”, almost saturating ψ production. We had thought that we understood $c\bar{c}$ production at this energy . . . but it’s pretty clear that we don’t. Tomasz Skwarnicki will have something to say about this, and other developments in charmonia, in the next presentation.¹⁰

1.2. *What I Am Talking About*

After discussing the problems of obtaining clean new physics signatures in the charm sector (Sec. 2), the largest part of the talk treats $D^0 - \bar{D}^0$ mixing searches (Sec. 3); there are important new results on both y_{CP} (Sec 3.3) and $D^0 \rightarrow K^+\pi^-$ (Sec. 3.4). The first CPT and Lorentz invariance violation study in charm has recently been published, and we discuss it briefly (Sec. 4). The remainder of the talk is given over to searches for rare and forbidden decays (Sec. 5). There are new results from BaBar, Belle, CDF, CLEO, and FOCUS—including, as I say, a first observation—but let’s not get ahead of ourselves.

2. Finding Clear New Physics Signatures

The difficulty with finding a clear signature of New Physics in the charm sector is this: it can be hard to know what the Standard Model (SM) prediction is. One way of thinking about the problem is to consider the masses of the quarks.

- The up and down quark masses are both small compared to the hadronic mass scale: $m_u < m_d \ll \lambda_{QCD}$.^b Isospin is therefore a rather good symmetry, and (including now the strange quark) $SU(3)$ of flavor, while broken, is useful.
- At the other extreme, the beauty quark has $m_b > \lambda_{QCD}$, and can be considered as a high-energy physics “particle”: a “billiard ball with quantum numbers attached”. One can think in terms of the Feynman diagrams, in b -sector processes, and not be too seriously misled.
- The charm quark lies between the two extremes: $m_c \gtrsim \lambda_{QCD}$, neither light nor truly heavy.

The awkwardness of the charm mass thus puts limits on both symmetry- and quark-based thinking as guides to charm physics. If light hadron work is like swimming in the ocean, and b -physics is like flying through the air, then in charm studies one is wading knee-deep through the brown muck.

One should really think in terms of hadrons, not quarks, in charm. So-called “long-distance” contributions are important in many processes: quark loops are typically suppressed, so that hadronic processes take a leading role. These are usually difficult to calculate, especially as the charm mass lies in the resonance region. So if some parameter is supposed to be small, but observed to be large, one should be cautious before claiming new physics: perhaps the Standard Model contribution has just been miscalculated. As discussed in Sec. 1.1, there have already been two major surprises in the last two years.

3. $D^0 - \bar{D}^0$ Mixing

3.1. *Mixing in the Standard Model and Beyond*

There are particular pitfalls in the interpretation of charm mixing searches. The SM box diagrams for mixing (e.g. Fig. 1) are doubly Cabibbo-suppressed and suffer from very efficient cancellations (the GIM mechanism): the expected mixing rate due to such processes is negligible. Since most new physics scenarios introduce new particles that couple to the SM fields, they induce new loop diagrams such as Fig. 2,

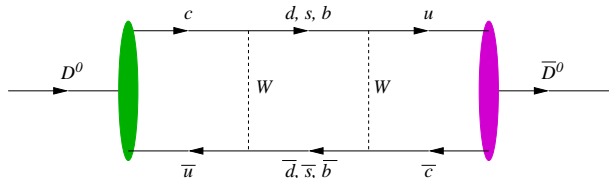


Figure 1. Box diagram for $D^0 - \bar{D}^0$ mixing in the SM.

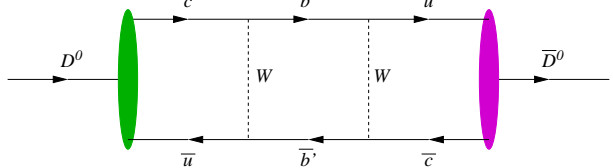


Figure 2. Box diagram for $D^0 - \bar{D}^0$ mixing in a New Physics model with an extra down-type quark.

with no (or a lesser degree of) cancellations. The result is an enhancement of the mass splitting of the $D^0 - \bar{D}^0$ eigenstates, $x \equiv \Delta M/\Gamma$; hence the common statement that “ $D^0 - \bar{D}^0$ mixing with measurable x is a signal of New Physics”.

As discussed in the previous section, however, hadronic processes cannot be neglected. Final states common to D^0 and \bar{D}^0 , such as $K\bar{K}$, $\pi\pi$, $K\pi$ and $\bar{K}\pi$, couple the two neutral D ’s (Fig. 3); such contributions cancel in the $SU(3)_F$ limit, but to the extent that $SU(3)$ of flavor is broken, they induce mixing. One might suppose that only the lifetime splitting parameter $y \equiv \Delta\Gamma/2\Gamma$ would be affected, as the intermediate states are real. The true situation is more complicated. To the extent that quark-hadron duality holds, mixing can be estimated using the Operator Product Expansion: a recent study¹¹ finds $x \sim y \sim O(10^{-3})$. An alternative approach¹² relying directly on hadronic intermediate states suggests that y may be as large as $O(1\%)$. So as far as x and y are concerned, mixing provides a clean new physics signal only if $x \gg y \sim 10^{-3}$.

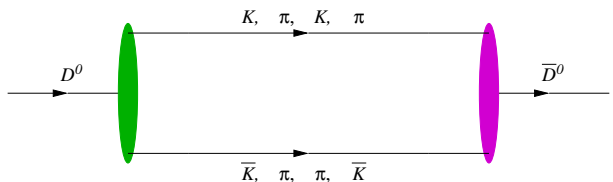


Figure 3. Sample diagram for $D^0 - \bar{D}^0$ mixing due to common hadronic final states.

^bWe set aside the related fact that m_u and m_d are elements of the theory, rather than straightforward “observations”.

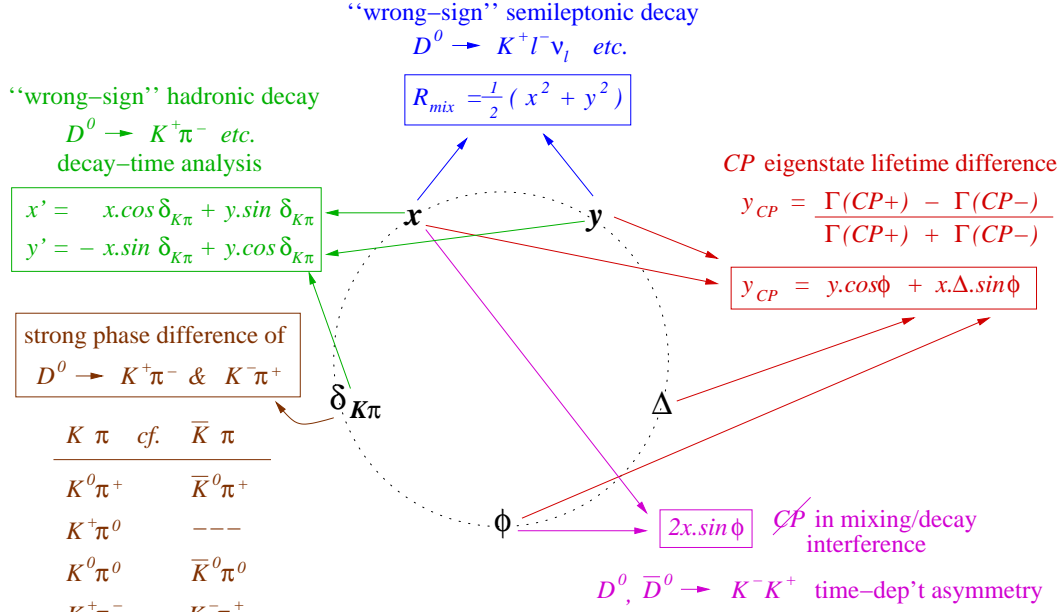


Figure 4. Five parameters describing $D^0 - \bar{D}^0$ mixing, and their relationship with quantities measured in experiment.

3.2. Mixing Parameters & Measurements

The full parameter space for mixing is more rich than (x, y) : some important parameters are shown in Fig. 4, together with experimentally measurable quantities. The parameters are poorly-known: the strong phase difference $\delta_{K\pi}$ between $D^0 \rightarrow K^+ \pi^-$ and $K^- \pi^+$ amplitudes is unconstrained, as is the difference in particle content of the eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, $\Delta = (|p|^2 - |q|^2)/(|p|^2 + |q|^2)$. But the news is not all bad. This year has seen the first measurements relevant to the CP violating phase $\phi = \arg(q\mathcal{A}(\bar{D}^0 \rightarrow K^- K^+)/p\mathcal{A}(D^0 \rightarrow K^- K^+))$ (Sec. 3.3.6), as well as a major new analysis of $D^0 \rightarrow K^+ \pi^-$ (Sec. 3.4).

3.3. Mixing: Lifetime Difference, y_{CP} , and CP Violation

The most popular measurement in recent years, however, has been y_{CP} . Defined as the normalized lifetime difference of the $D^0 - \bar{D}^0$ CP eigenstates, it is typically measured using the non-eigenstate decay $D^0 \rightarrow K^- \pi^+$ as a convenient reference:

$$y_{CP} \equiv \frac{\Gamma(CP+) - \Gamma(CP-)}{\Gamma(CP+) + \Gamma(CP-)} \approx \frac{\tau(D^0 \rightarrow K^- \pi^+)}{\tau(D^0 \rightarrow K^- K^+)} - 1$$

$$= y \cos \phi + x \Delta \sin \phi,$$

where the last relation holds for small values of the parameters. In the CP-conserving limit $\phi = 0$ and $\Delta = 0$, so $y_{CP} = y$, as one would expect. In this limit y_{CP} is not a new-physics search parameter (since new particles are expected to affect x ; Sec. 3.1) but a tool for measuring the level of mixing due to the SM.

3.3.1. y_{CP} : the FOCUS measurement (2000)

Three years ago, the FOCUS collaboration measured y_{CP} using a relatively clean sample of 10,000 $D^0 \rightarrow K^- K^+$ events,^c and a $K^- \pi^+$ sample ten times that size.¹³ Both inclusive and D^* -tagged decays were used, under FOCUS-standard reconstruction, particle identification, and vertex detachment cuts; the result was obtained from a binned maximum-likelihood (ML) fit to the distributions of *reduced proper time* $t' \equiv (l - N\sigma_l)/\beta\gamma c$, where l, σ_l are the D^0 decay length and its error, and N the minimum required detachment of the production and decay vertices.

The result was surprisingly large: $y_{CP} = (3.42 \pm 1.39 \pm 0.74)\%$, over 2σ away from zero. There was considerable excitement at the thought that charm mixing might be within our grasp, partly due to the usual association of mixing with new physics. But as

^cInclusion of charge-conjugate modes is implied throughout, unless the context makes clear that they are treated separately.

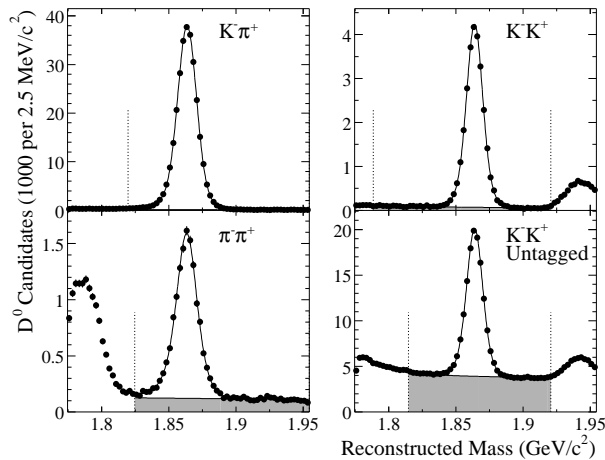


Figure 5. BaBar y_{CP} analysis:¹⁶ invariant mass distribution for data (points), projection of the fit (curve), and fitted background component (shaded) for the four samples.

discussed above, the most natural interpretation of percent-level y_{CP} would be a large lifetime difference parameter y , due to Standard Model effects. The new physics interpretation was possible, but somewhat forced: mixing with $x \gg y$ and large CP violation, $\sin \phi \sim O(1)$, $\Delta \sim O(1)$.

3.3.2. y_{CP} : Belle and CLEO (2002)

New measurements have followed in short order, using D^0 produced in $e^+e^- \rightarrow c\bar{c}$ interactions at the B -factories. Belle¹⁴ used a sample somewhat larger and cleaner than that of FOCUS, performing an unbinned maximum-likelihood (UML) fit to inclusive $D^0 \rightarrow K^-\pi^+$ and K^+K^- decay time distributions, and measuring $y_{CP} = (-0.5 \pm 1.0_{-0.8}^{+0.7})\%$. CLEO¹⁵ used a smaller sample (the 9.0 fb^{-1} CLEO II.V run), required a D^* -tag, and added $D^0 \rightarrow \pi^+\pi^-$ to the usual modes; they measured $y_{CP} = (-1.2 \pm 2.5 \pm 1.4)\%$. Both results are manifestly consistent with zero, and each other—and the fact that both are negative has led many to discount the FOCUS result. But it’s worth noting that the average y_{CP} from the three is positive, and $\sim 1\%$.

3.3.3. y_{CP} : BaBar (2003)

This year BaBar has released a comprehensive y_{CP} measurement¹⁶ based on 91 fb^{-1} of data including both D^* -tagged $D^0 \rightarrow K^-\pi^+$, K^+K^- , $\pi^+\pi^-$ events, and inclusive $D^0 \rightarrow K^+K^-$. As usual in e^+e^- analyses, backgrounds are suppressed by a

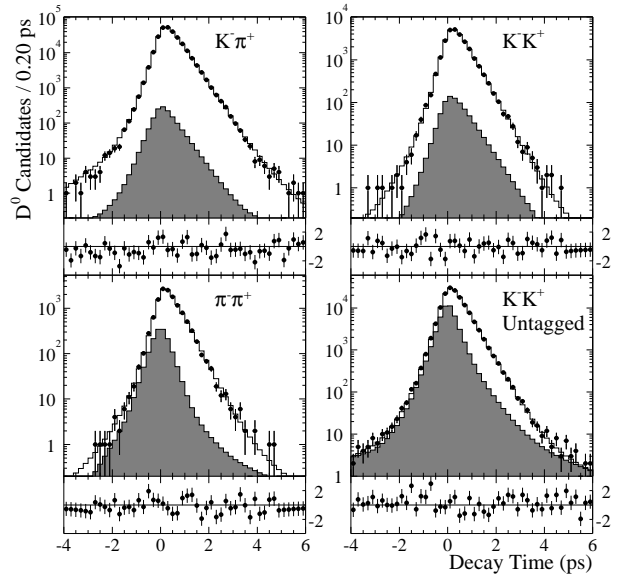


Figure 6. BaBar y_{CP} analysis:¹⁶ proper time distribution for data (points), UML fit projection (open histogram), and fitted background component (shaded) for the four samples. The points beneath each plot show the bin-by-bin differences between the data and the fit, divided by the statistical error.

center-of-mass momentum cut and vertex quality cut on the D^0 , particle identification (PID) cuts on the daughter tracks, and (for the D^* -tagged samples) cuts on the D^* -decay pion (the “slow pion”). The resulting D^0 samples are shown in Fig. 5. For each sample, the fitted mass distribution is used to determine the event-by-event probability that a D^0 candidate belongs to the signal, as opposed to the background under the peak. This probability is then included in the likelihood function for each event in an UML fit to the proper-time distribution.

These distributions, and the results of the fits for each sample, are shown in Fig. 6. In each fit, the assumed “underlying” distributions of both signal and background are convolved with resolution functions based on a sum of gaussians: most of these terms have widths of the form $S\sigma_t^i$, where σ_t^i is the event-by-event proper time error, and S is a scaling factor, meant to account for deficiencies in modelling of the detector, etc.. This method is common to the earlier Belle¹⁴ and CLEO¹⁵ analyses and reflects a consensus on time-distribution fitting at the B -factories.

A blind analysis was performed to obtain the mixing parameter: the weighted average over the four modes is $y_{CP} = (0.8 \pm 0.4_{-0.4}^{+0.5})\%$, the most precise measurement to date.

3.3.4. y_{CP} : Belle, D^* -tagged (2003)

A new analysis from Belle, contributed to this symposium,¹⁷ takes a different approach. The idea is to find a robust resolution function which does not rely on the estimated proper-time error: this allows binned ML fits to be used throughout, so that the goodness-of-fit can be explicitly checked. D^* -tagged $D^0 \rightarrow K^- \pi^+$ and $K^+ K^-$ events from the full Belle dataset of 158 fb^{-1} are used, subject to standard reconstruction cuts, and the requirement that the proper time be well-measured.

The D^0 lifetime, y_{CP} , and the parameters of the proper-time resolution function are all determined in a single simultaneous binned ML fit to the $K^- \pi^+$ and $K^+ K^-$ samples. The form of the resolution function is simple: a sum of five gaussians with a common mean, fixed relative normalizations, and floating widths. The gaussian widths for $K^+ K^-$ are constrained to be the same as those for $K^- \pi^+$, up to a single scale factor which is common to all terms. This parameterization has been studied using Monte Carlo (MC) data, and proves to be very stable: all values determined in a full decay-time fit match those fitted to the true resolution function, within their relative errors (Table 1).

Table 1. Belle y_{CP} analysis:¹⁷ comparison of the parameters obtained in MC from a fit to the resolution function, using MC truth information (3rd column) and from the decay time fit, using reconstructed information only (4th column). The fractions of the five gaussian terms, fixed from the resolution function fit, are also shown (2nd column).

par.	fraction (%)	fitted values (fs; except α)	
		resolution fit	lifetime fit
σ_1	26.1	95.1 ± 1.3	94.4 ± 1.7
σ_2	50.4	177.0 ± 2.2	179.0 ± 1.2
σ_3	19.8	328.7 ± 7.4	328.2 ± 2.2
σ_4	3.1	675.7 ± 24.9	664.4 ± 8.5
σ_5	0.6	2199 ± 95	2225 ± 70
X_0	[common shift]	-1.51 ± 0.22	-0.95 ± 0.54
α	[$K\pi \rightarrow KK$ scale]	1.043 ± 0.004	1.042 ± 0.007

The proper time distribution for data is shown in Fig. 7, together with the result of the binned ML fit; the confidence level is 94%. (All fits in the analysis have an acceptable confidence level.) The fit returns a D^0 lifetime (from the $K^- \pi^+$ sample) of $412.6 \pm 1.1 \text{ fs}$, consistent with the world average,¹⁸ and a mixing parameter $y_{CP} = (1.15 \pm 0.69 \pm 0.38)\%$; the result is preliminary.

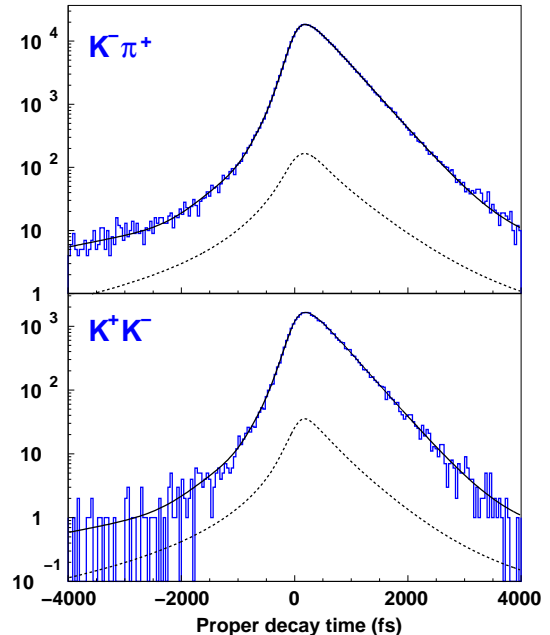


Figure 7. Belle y_{CP} analysis:¹⁷ proper time distribution for data (histogram), binned ML fit (solid curve), and background component (dashed), for the $K^- \pi^+$ (upper) and $K^+ K^-$ (lower) samples.

3.3.5. y_{CP} : summary of results

For completeness, the y_{CP} results are summarized in Table 2. Note the dominance of the numbers from Belle (the tagged result,¹⁷ as noted, is preliminary) and BaBar. The implications of these results were not addressed at this point in the talk, but in the Discussion at the end. We preserve this order here.

Table 2. Summary of y_{CP} results.

Experiment	y_{CP} (%)
E791 ¹⁹	$0.8 \pm 2.9 \pm 1.0$
FOCUS ¹³	$3.4 \pm 1.4 \pm 0.7$
Belle, untagged ¹⁴	$-0.5 \pm 1.0 \pm 0.8$
CLEO ¹⁵	$-1.2 \pm 2.5 \pm 1.4$
BaBar ¹⁶	$0.8 \pm 0.4^{+0.5}_{-0.4}$
Belle, tagged ¹⁷	$1.2 \pm 0.7 \pm 0.4$

3.3.6. “ $y_{CP}++$ ”: D^0 - \bar{D}^0 mixing and CPV

In y_{CP} analyses based on D^* -tagged samples, a CP-violation study comes “for free”: one can simply compare the lifetime of $K^+ K^-$ events with different flavor D -tags, within the same analysis framework

used for y_{CP} . Belle¹⁷ defines a parameter

$$A_{\Gamma} \equiv \frac{\hat{\Gamma}(D \rightarrow KK) - \hat{\Gamma}(\bar{D} \rightarrow KK)}{\hat{\Gamma}(D \rightarrow KK) + \hat{\Gamma}(\bar{D} \rightarrow KK)} \\ \approx -\Delta \cdot y \cos \phi - x \sin \phi,$$

where the notation $\hat{\Gamma}$ for “effective lifetime” recognises that an exponential is being fitted to distributions which may not be strictly exponential. In the absence of CP violation in mixing, i.e. $\Delta = 0$, the asymmetry parameter $A_{\Gamma} = -x \sin \phi$, measuring the CP violating phase $\phi = \arg(q\bar{A}/pA)$ due to the interference of decay and mixing.^d The “ ΔY ” parameter of BaBar¹⁶ is similar, differing by a factor of $(1 + y_{\text{CP}})$. Most systematic errors cancel due to the use of a common final state. The experiments find the following values,

$$\Delta Y = (-0.8 \pm 0.6 \pm 0.2)\% \text{ (BaBar)}$$

$$A_{\Gamma} = (-0.2 \pm 0.6 \pm 0.3)\% \text{ (Belle prelim.)},$$

consistent with zero; the measurements are statistically dominated and will continue to improve for the life of the B -factories.

Unlike mixing in general, CP violation associated with mixing is a robust new physics signal.²⁰ all charm mixing phenomena in the SM are dominated by the first two generations, so CP violation must be small. Even for $x \sim y = O(1\%)$, we expect $A_{\Gamma} \lesssim 10^{-4}$. So any significant non-zero measurement by this technique would be evidence of new physics contributing to mixing. One can imagine a scenario where *both* Standard Model and new physics processes lead to percent-level values of the mixing parameters (y and x respectively), and the new physics contribution leads to 30%-level CP violation: evidence for both SM mixing (via y_{CP}) and non-SM processes (via A_{Γ}) would emerge by the end of the B -factory era.

3.4. *Mixing: $D^0 \rightarrow K^+\pi^-$*

Another new BaBar analysis,²¹ of $D^0 \rightarrow K^+\pi^-$ decays, has brought hadronic mixing analyses back into prominence. Pioneered by CLEO,²² the sophisticated analysis method is sensitive to both mass- (x) and lifetime-splitting (y) of the neutral D eigenstates, and has been considered the technique of

choice for e^+e^- machines. The BaBar analysis has been gestating for some time—there were preliminary presentations (without final fit results) two years ago—and the related analysis at Belle is still underway, with only an intermediate result (the “wrong-sign rate” for $K\pi$) in the public domain.²³

3.4.1. $D^0 \rightarrow K^+\pi^-$: *the analysis method*

“Wrong-sign” hadronic decays such as $D^0 \rightarrow K^+\pi^-$ occur via two paths: mixing $D^0 \rightarrow \bar{D}^0$ followed by Cabibbo-favoured decay $\bar{D}^0 \rightarrow K^+\pi^-$, and directly by doubly-Cabibbo-suppressed (DCS) decay $D^0 \rightarrow K^+\pi^-$. The DCS decay thus forms a background to the mixing signal, and the two must be separated by reconstructing the decay time of the D^0 and exploiting the different time distributions: e^{-t} for DCS decay and t^2e^{-t} for mixing, where the proper time t is in units of the D^0 lifetime. The interference term between the DCS and mixing paths, which goes as te^{-t} , cannot be neglected:²⁴ in fact it provides most of the mixing sensitivity, since the DCS rate is much larger than the mixing rate and the interference term is thus intermediate in size. A complication of the method is that this term is proportional, not to the lifetime difference parameter y , but to the quantity $y' \equiv y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$ which has been “rotated” by the strong phase difference $\delta_{K\pi}$ between the $D^0 \rightarrow K^+\pi^-$ and $K^-\pi^+$ decays.

The subtle difference in time distributions (e^{-t} , te^{-t} , t^2e^{-t}) means that the time structure of background events must be well-understood to avoid faking a mixing signal. This is important as background levels are relatively high. The method used by CLEO,²² which has been followed by both BaBar²¹ and Belle,²³ is to (1) tag the initial D flavor by reconstructing $D^{*+} \rightarrow D^0\pi^+$; (2) categorize the backgrounds according to their proper-time distribution; (3) measure their relative levels by fitting the data distribution in (M, Q) where M is the $K\pi$ mass and $Q = M(K^+\pi^-\pi^+) - M(K^+\pi^-) - m_{\pi}$ is the energy release in D^{*+} decay;^e and (4) fix the background levels in the fit to proper time. This is difficult, but manageable, and CLEO reported limits at the 95% confidence level of $\frac{1}{2}x'^2 < 0.041\%$ and $-5.8\% < y' < 1.0\%$ based on this method.

^dThe analysis is thus a close analogue of the $B^0/\bar{B}^0 \rightarrow \psi K_S^0$ analysis in the b -sector, measuring $\sin 2\phi_1 [\equiv \sin 2\beta]$.

^eBaBar uses $\delta m \equiv M(K^+\pi^-\pi^+) - M(K^+\pi^-)$, which differs from Q by a constant.

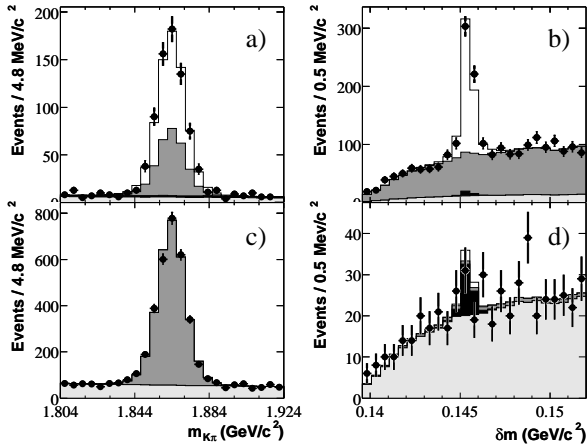


Figure 8. BaBar $D^0 \rightarrow K^+\pi^-$ analysis:²¹ (a,c) $K^+\pi^-$ mass and (b,d) $D^{*+} - D^0$ mass-difference distributions, for (a,b) signal- and (c,d) background-dominated regions. Shown are the data (points), the projection of the fit (open histogram), and the fitted combinatorial (light), unassociated pion (dark), and double-misidentification background (black).

3.4.2. $D^0 \rightarrow K^+\pi^-$: the BaBar analysis

The BaBar analysis follows the CLEO model closely, but with a larger data sample (57.1 fb^{-1}), lower backgrounds (due to BaBar’s superior PID), and a data selection and fitting procedure finalized while remaining “blind” to the mixing results. The $K^+\pi^-$ distributions are shown in Fig. 8: background events are divided into combinatorial, true- D^0 -plus-unassociated-pion, and double-misidentification categories. This last type, where $K^-\pi^+$ is misidentified as π^-K^+ , is small but significant: see Fig. 8(b,d). Such events are retained to avoid any distortion of the other backgrounds due to targeted rejection cuts. The fit used to establish the background levels describes the data well.

The mixing parameters are then determined using unbinned, extended maximum-likelihood fits to the $D^0 \rightarrow K^+\pi^-$ (“wrong sign”) and $D^0 \rightarrow K^-\pi^+$ (“right sign”) data. The likelihood terms for the signal and various background time distributions are formed from underlying distributions (exponentials or delta functions) convolved with event-dependent resolution functions similar to those of the y_{CP} analysis (Sec. 3.3.3); the event-by-event signal- and background-fractions are determined from the $(m_{K\pi}, \delta m)$ fit. The results are shown in Fig. 9 for regions in $(m_{K\pi}, \delta m)$ dominated by signal (Fig. 9(a)) and background (Fig. 9(b)) events.

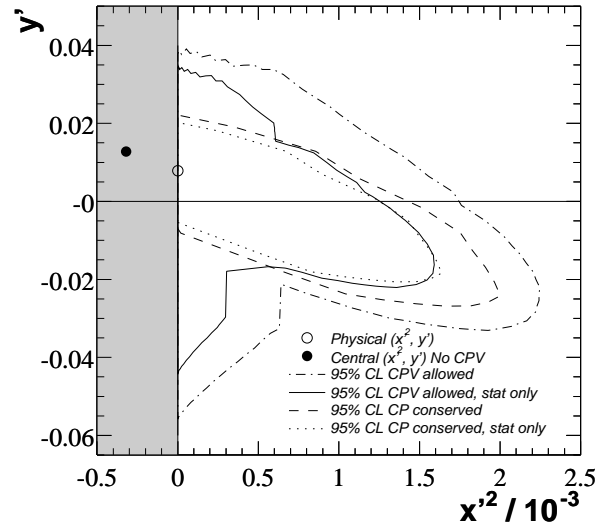


Figure 10. BaBar $D^0 \rightarrow K^+\pi^-$ analysis:²¹ fit results and confidence intervals for the mixing parameters (x'^2, y') .

Four overall fits allowing DCS decay only; DCS decay and CP violation (treating D^0 and \bar{D}^0 separately); DCS decay and mixing, but no CP violation; and all three effects, are performed: the results are shown in Table 3. No evidence for mixing or CP violation is found. A slightly negative (and thus unphysical) value of x'^2 is preferred by the fit: this is taken into account in reporting the results.

Table 3. BaBar $D^0 \rightarrow K^+\pi^-$ analysis:²¹ parameters returned by the full fit to D^0 , \bar{D}^0 , and combined samples.

Fit case	Parameter	Fit result ($/10^{-3}$)		
		D^0	\bar{D}^0	$D^0 + \bar{D}^0$
Mixing allowed	$R_{WS}^{(\pm)}$	3.9	3.2	3.6
	$x'^{(\pm)2}$	-0.79	-0.17	-0.32
	$y'^{(\pm)}$	17	12	13
No mixing	$R_{WS}^{(\pm)}$	3.9	3.2	3.6

A rather careful procedure based on toy MC experiments is used to set frequentist confidence intervals in the fitting parameters x'^2 and y' : the results are shown in Fig. 10. A remarkable feature of the analysis is that the allowed region in (x'^2, y') is comparable in size to that of CLEO, despite the larger and cleaner dataset. Simulations by both BaBar²⁵ and Belle show that for a given experiment, when the preferred value has $y' > 0$ (as in the BaBar analysis), the allowed region becomes large compared to that when the data prefers $y' < 0$ (as in CLEO’s

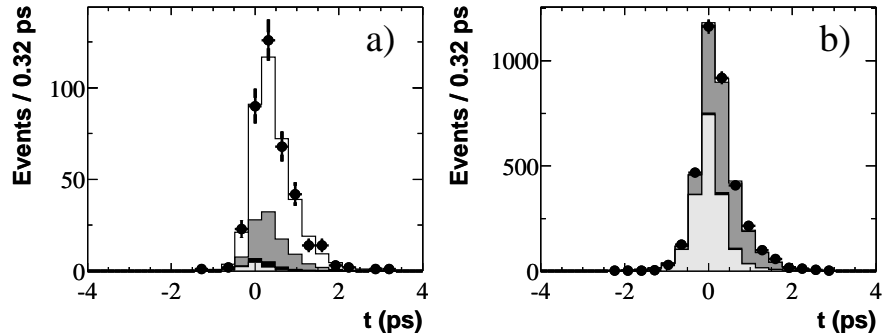


Figure 9. BaBar $D^0 \rightarrow K^+\pi^-$ analysis:²¹ proper time distributions for (a) signal- and (b) background-dominated regions. Shown are the data (points), the projection of the fit (open histogram), and the fitted combinatorial (light), unassociated pion (dark), and double-misidentification background (black).

case).^f It is thus almost meaningless to “average” the results of experiments whose preferred values fall in different y' regions.

3.5. Mixing: Issues and Future Measurements

A combined $D^0 \rightarrow K^+\pi^-$ result will require a combined analysis: perhaps there is a need for a joint working group, or at least detailed consultation between experiments, as we enter the CLEO-c era. Comparison of (x', y') and y_{CP} results is more complicated still. The strong phase difference $\delta_{K\pi}$, bequeathed us by the mischievous god of the color force, must first be measured: a significant shift might occur due to final-state interactions (FSI), shown to be significant in $D \rightarrow hh$ decays by isospin analyses of CLEO²⁶ and FOCUS;²⁷ the latter study provides evidence for inelastic FSI.

The default option is to wait for results from the CLEO-c run at the $\psi(3770)$, as one of the analyses exploiting the coherent $D^0\bar{D}^0$ state promises an error in $\cos\delta_{K\pi}$ of order ± 0.05 .^{28,29} The other option is a complete measurement of the DCS $D \rightarrow K\pi$ decays, of which only $D^0 \rightarrow K^+\pi^-$ is currently known. CLEO has recently placed a limit on $D^+ \rightarrow K^+\pi^0$,²⁶

^fThis may also be understood in qualitative terms using the proper time distribution for wrong-sign decays,

$$e^{-t} \left(R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2 \right),$$

where R_D is the DCS decay rate. For $y' < 0$ there is a partial cancellation between the interference ($\propto te^{-t}$) and mixing ($\propto t^2e^{-t}$) terms, and the fit becomes sensitive to small changes in both the x'^2 and y' parameters. For $y' > 0$, no such cancellation takes place.

a measurement is presumably within the reach of the other B -factory experiments. Measurement of $D^{+,0} \rightarrow K^0\pi^{+,0}$ rates relies on the measurement of $D^{+,0} \rightarrow K_L^0\pi^{+,0}$ decays: the asymmetry with the corresponding K_S^0 mode is proportional to the interference between decay amplitudes via K^0 and \bar{K}^0 . A method for this measurement has been demonstrated by Belle, with a preliminary result for $D^0 \rightarrow K_L^0\pi^0$.³⁰

A promising new analysis method exploits the $D^0 \rightarrow K_S^0\pi^+\pi^-$ final state: Cabibbo-favoured (e.g. $K^{*+}\pi^-$) and doubly-suppressed ($K^{*+}\pi^-$) decays interfere, allowing measurement of the strong phase differences for the various resonant submodes; a study of time-dependence then yields the mixing parameters x and y . This method has the advantages of superior scaling properties (the fit measures x rather than x'^2) and sensitivity to the sign of the mass splitting, in addition to the measurement of phases. It is, however, unproven. It has been championed by CLEO, who have measured the resonant substructure of the decay;³¹ a mixing study will presumably require the large samples available at the other B -factories. Those samples may also provide useful sensitivity from semileptonic decays, which have fallen out of favor, although there is an interesting unpublished $D^0 \rightarrow K^{(*)+}\ell^-\bar{\nu}_\ell$ analysis by CLEO.³²

Fits for CP violating effects in mixing are now routine, and will increasingly become the main focus of study. By the next Lepton Photon meeting, the other major development will be CLEO-c analyses exploiting opposite-side tagging, geometric signal-to-background ratios, and a coherent initial state leading to new mixing and CP violation observables.

4. CPT and Lorentz Invariance Violation

Even more general analyses would allow for violation of CPT symmetry, a manifest signal of new physics. While such studies have been carried out for kaons and B mesons, no CPT violation search had been performed in the charm sector until the recent FOCUS analysis.³³ Using D^* -tagged $D^0 \rightarrow K^- \pi^+$ decays, they searched for indirect CPT violation parametrized by $\xi \equiv (\Lambda_{11} - \Lambda_{22})/(\lambda_1 - \lambda_2)$, where Λ is the 2×2 effective Hamiltonian governing the time evolution of neutral D mesons, Λ_{ii} are its diagonal elements, and λ_j its eigenvalues. The measured quantity is the time-dependent rate asymmetry

$$A_{\text{CPT}}(t) \equiv \frac{\Gamma(\overline{D}^0 \rightarrow K^+ \pi^-) - \Gamma(D^0 \rightarrow K^- \pi^+)}{\Gamma(\overline{D}^0 \rightarrow K^+ \pi^-) + \Gamma(D^0 \rightarrow K^- \pi^+)},$$

which reduces to $(\text{Re}(\xi)y - \text{Im}(\xi)x)\Gamma t$ for $xt, yt \ll 1/\Gamma$; x and y are the mixing parameters discussed above. FOCUS finds $(\text{Re}(\xi)y - \text{Im}(\xi)x) = 0.0083 \pm 0.0065 \pm 0.0041$, with a 95% confidence interval $-0.0068 < (\text{Re}(\xi)y - \text{Im}(\xi)x) < 0.0234$, consistent with zero. Their paper cites as an example the case where D^0 and \overline{D}^0 mix with parameters $(x, y) = (0.0, 0.01)$: in this scenario, $0.68 < \text{Re} \xi < 2.34$.

Within a formalism that allows for violation of Lorentz invariance, ξ may depend on the vector momentum of the studied particles, and on sidereal time; the relation is a function of parameters³⁴ $\Delta a_{0,X,Y,Z}$, where (X, Y, Z) is a non-rotating coordinate system. FOCUS fits for these quantities by measuring the CPT-violating parameter ξ in bins of sidereal time: we can summarize the (complicated) result by noting that the various $|\Delta a_\mu| < O(10^{-12})$ GeV at 95% confidence for the case $(x, y, \delta_{K\pi}) = (0.01, 0.01, 15^\circ)$. This is to be compared with limits of order 10^{-21} for the $K^0\text{-}\overline{K}^0$ system: the difference reflects both the size of the available data samples and the relative strength of mixing in the two systems. The Δa_μ may in principle vary with flavor, so this measurement is important for completeness, even though the sensitivity does not compete with that for kaons.

5. Rare and Forbidden Decays

Moving to less exotic possibilities, flavor-changing neutral currents (FCNC) have not yet been observed in the charm sector. As with mixing, the SM parton-level loop contributions are subject to powerful cancellations, and long-distance contributions dominate.

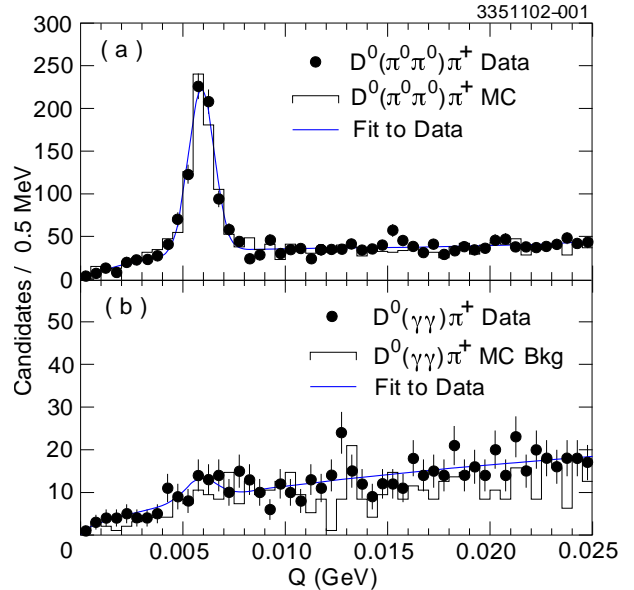


Figure 11. CLEO $D^0 \rightarrow \gamma\gamma$ analysis:³⁶ $D^{*+} - D^0$ mass-difference distributions for (a) $D^0 \rightarrow \pi^0\pi^0$ and (b) $D^0 \rightarrow \gamma\gamma$.

As a result, it can be difficult to calculate the SM expectation with certainty. The best new physics signals are those decays with extremely small predicted rates, or special features which allow SM and non-SM contributions to be distinguished.

The decay $D^0 \rightarrow \gamma\gamma$, with an expected branching fraction of order 10^{-8} , is thus a new physics signal (Sec. 5.1); but $D^0 \rightarrow \mu^+\mu^-$ (Sec. 5.2), whose predicted rate is five orders of magnitude smaller, is a more reliable one.³⁵ In the case of decays $D \rightarrow h\ell^+\ell^-$, the most robust new physics signal is not the decay rate, but the dilepton mass spectrum, which exhibits marked differences between SM and new-physics predictions (Sec. 5.3). And in each case, variant modes violating lepton flavor or number conservation can be added “for free” to the analysis, in the spirit of a lamp-post search: there is no uncertainty on Standard Model predictions of zero. We consider each of these cases in turn, before treating decays $D^0 \rightarrow V\gamma$ in the final section (Sec. 5.4).

5.1. $D^0 \rightarrow \gamma\gamma$ (CLEO)

Decays to photons have very small contributions from parton-level processes, but significant ones from the vector meson dominance (VMD) mechanism: $\mathcal{B}(D^0 \rightarrow \gamma\gamma)$ would be $\sim 3 \times 10^{-11}$ if only short-distance mechanisms contributed, but is expected to

be of order 10^{-8} due to long-distance SM processes. This mode has not previously been studied. CLEO has recently used $D^{*+} \rightarrow D^0 \pi^+$ events in 13.8 fb^{-1} of data to conduct a $D^0 \rightarrow \gamma\gamma$ search, normalizing to the $D^0 \rightarrow \pi^0 \pi^0$ mode.³⁶ Under standard cuts, augmented with a $\pi^0 \rightarrow \gamma\gamma$ veto on the photons forming the $D^0 \rightarrow \gamma\gamma$ candidates, they accumulate fairly clean event samples and then fit the distribution of energy release Q from the D^* decay, to keep differences between the $\pi^0 \pi^0$ and $\gamma\gamma$ modes to a minimum. The results are shown in Fig. 11: the agreement between the data and the MC simulation is remarkable.

A limit $\mathcal{B}(D^0 \rightarrow \gamma\gamma) < 2.9 \times 10^{-5}$ is found at the 90% confidence level, some three orders of magnitude above the SM prediction. There is thus some room for a new physics signal if future experiments can improve on CLEO’s sensitivity.

5.2. $D^0 \rightarrow \mu^+ \mu^-$ (CDF)

The expected rate for $D^0 \rightarrow \mu^+ \mu^-$ is much smaller, $O(10^{-13})$, whereas R-parity violating (RPV) Supersymmetry could lead to a branching fraction as high as 3.5×10^{-6} , just smaller than the previous experimental bound.³⁵ The dimuon decay is thus a straightforward new-physics search mode. Using their upgraded detector and trigger system, which allows them to select a charm decay sample, CDF have conducted a search for this mode in the early Run II data.³⁷ With a fairly straightforward blind analysis, using D^* -tagged events and $D^0 \rightarrow \pi^+ \pi^-$ decay as a normalization mode, they observe no $\mu^+ \mu^-$ events and set a limit $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 2.4 \times 10^{-6}$ at 90% confidence, improving on the previous bound by a factor of two. The $O(1)$ event background estimate relies on interpolation from the sidebands—events with true muon(s) dominate over the misidentification background—and will need to be better understood to significantly improve the limit. Presumably this is achievable, and improvements to this channel will depend on the progress of Run II data-taking.

5.3. $D \rightarrow h \ell \ell$ (FOCUS)

The only analysis of a “basket” of rare decay modes in recent times is by FOCUS, who have searched for decays $D_{(s)}^+ \rightarrow h^\pm \mu \mu$, where $h^\pm = \pi^\pm, K^\pm$.³⁸ For definiteness we will take $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ as an example. The predicted SM rate for this decay is $O(10^{-6})$, while (e.g.) the allowed R-parity violating

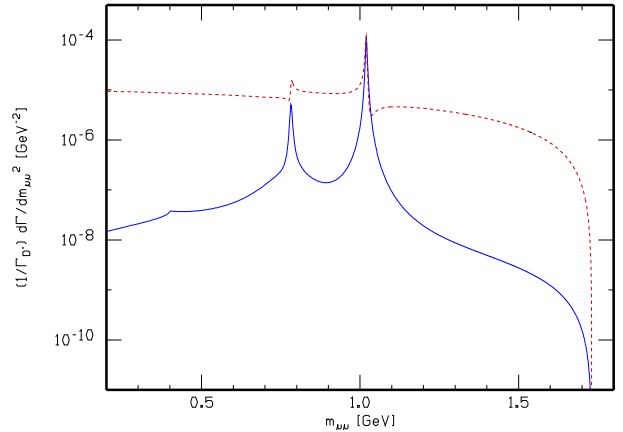


Figure 12. Predicted³⁵ dimuon mass distributions $M(\mu^+ \mu^-)$ for $D^+ \rightarrow \pi^+ \mu^+ \mu^-$. The solid line shows the sum of the short- and long-distance contributions in the SM; the dotted line, the R-parity violating contribution from SUSY at the level allowed prior to the FOCUS measurement—see the text.

contribution,³⁵ 15×10^{-6} , saturates the previous experimental limit.³⁹ There would therefore seem to be potential for further restriction of RPV parameters, but not for observation of a new physics signal.

The SM contribution, however, is dominated by the path $D^+ \rightarrow \pi^+ V \rightarrow \pi^+ \mu^+ \mu^-$, where the V are vector mesons. The predicted dimuon mass spectrum (Fig. 12) thus shows pronounced peaks at the ρ and ϕ masses, which dominate the SM rate. By contrast the spectrum for RPV is relatively flat, so that a new physics contribution comparable to or even below the SM contribution could be resolved by comparing the $M(\mu^+ \mu^-)$ distribution of observed events with the various predictions.

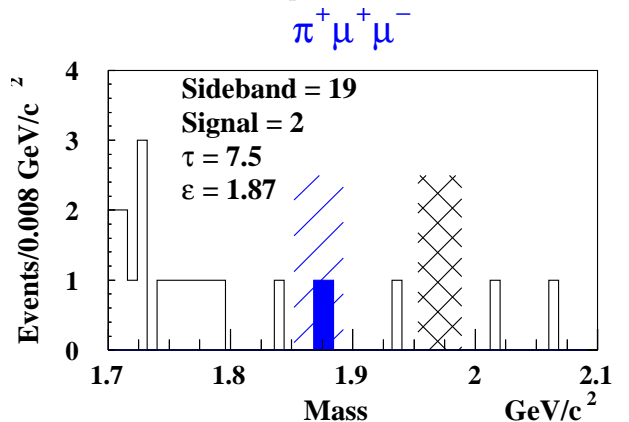


Figure 13. FOCUS $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ analysis:³⁸ the histogram shows selected events; the filled entry is in the signal region. The signal region (hatched) and the region used for sideband subtraction (cross-hatched) are also shown.

FOCUS is beginning to probe this region. A histogram of selected events for the $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ analysis is shown in Fig. 13, and results for all the modes are listed in Table 4. The analysis proceeds using standard FOCUS detached vertex, hadron- and muon-identification cuts; cut values are selected and background estimates calculated using a very careful “dual bootstrap” method, to minimise possible selection biases. No evidence is seen for any of the decay modes; existing limits are everywhere improved, in some cases by an order of magnitude. For the $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $D_s^+ \rightarrow \pi^+ \mu^+ \mu^-$ modes, the sensitivity is approaching the SM prediction.

Table 4. FOCUS $D \rightarrow h\ell\ell$ analysis:³⁸ measured limit on the branching fraction, SM prediction,⁴⁰ previous best limit,^{39,41} and expected CLEO-c sensitivity²⁹ for each mode. (D_s^+ sensitivities are scaled from those of D^+ and are not official CLEO-c numbers.) All entries are ($/10^{-6}$).

Mode	FOCUS	SM	Prev.	CLEO-c
$D^+ \rightarrow K^+ \mu^- \mu^+$	9.2	0.007	44	1.5
$D^+ \rightarrow K^- \mu^+ \mu^+$	13	-	120	1.5
$D^+ \rightarrow \pi^+ \mu^- \mu^+$	8.8	1.0	15	1.5
$D^+ \rightarrow \pi^- \mu^+ \mu^+$	4.8	-	17	1.5
$D_s^+ \rightarrow K^+ \mu^- \mu^+$	36	0.043	140	15
$D_s^+ \rightarrow K^- \mu^+ \mu^+$	13	-	180	15
$D_s^+ \rightarrow \pi^+ \mu^- \mu^+$	26	6.1	140	15
$D_s^+ \rightarrow \pi^- \mu^+ \mu^+$	29	-	82	15

Further progress is expected at CLEO-c, whose sensitivities²⁹ are also shown: an improvement by a factor $3 \sim 8$ is foreseen for the D^+ modes, reaching the SM expectation in the case of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ and therefore restricting further the RPV contribution. Any signal in the lepton-number violating modes $D_{(s)}^+ \rightarrow h^- \mu^+ \mu^+$, albeit unexpected, would of course be an observation of new physics.

5.4. $D^0 \rightarrow \phi\gamma, \phi\pi^0, \phi\eta$ (Belle)

Finally we turn to radiative decays $D^0 \rightarrow V\gamma$, another vector meson dominance process in the Standard Model. The Belle collaboration has conducted a search for $D^0 \rightarrow \phi\gamma$, exploiting double kaon identification in $\phi \rightarrow K^+ K^-$ to suppress backgrounds.⁴² Theoretical estimates for this mode,^{43,44} dominated by $D^0 \rightarrow VV' \rightarrow V\gamma$ (where the $V^{(\prime)}$ are vector mesons), are in the range $(0.04 \sim 3.4) \times 10^{-5}$, well below the previous limit of 1.9×10^{-4} but partially overlapping the sensitivity at the B -factories.

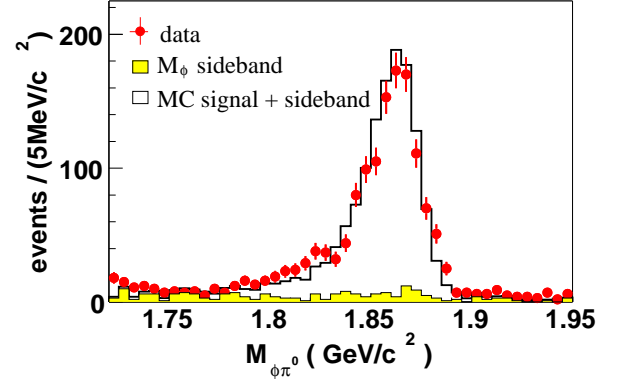


Figure 14. Belle $D^0 \rightarrow \phi\gamma, \phi\pi^0, \phi\eta$ analysis:⁴² $\phi\pi^0$ mass distribution for data (points) and MC (histogram); the ϕ -mass sideband is also shown (shaded).

D^* -tagging and cuts on the D^* momentum and γ energy are used to suppress the various combinatorial backgrounds. The dominant remaining background is due to the Cabibbo- and color-suppressed decays $D^0 \rightarrow \phi\pi^0$ and $\phi\eta$, which have not previously been observed. With analogous cuts to select $D^0 \rightarrow \phi\pi^0$ Belle sees a very clear signal in $M(\phi\pi^0)$ (Fig. 14) and the expected distribution of the helicity angle of the ϕ meson (not shown); the ϕ is polarized in the D^0 decay. A smaller but still clear signal of 31 ± 9.8 events is seen for $D^0 \rightarrow \phi\eta$, where a veto is imposed on photons for the $\eta \rightarrow \gamma\gamma$ candidate consistent with belonging to a $\pi^0 \rightarrow \gamma\gamma$ decay.

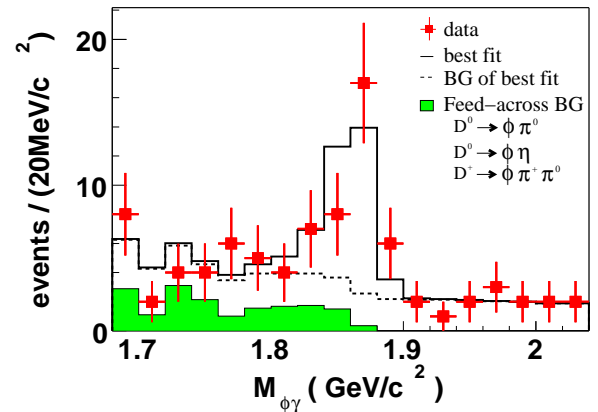


Figure 15. Belle $D^0 \rightarrow \phi\gamma, \phi\pi^0, \phi\eta$ analysis:⁴² $\phi\gamma$ mass distribution for data (points), the ML fit (open histogram), the background component of the fit (dashed), and the sum of $D^0 \rightarrow \phi\pi^0, \phi\eta$ and $D^+ \rightarrow \phi\pi^+\pi^0$ backgrounds (shaded).

The contribution of these decays to the $\phi\gamma$ spectrum can then be reliably estimated; it is suppressed by a helicity angle cut $|\cos\theta_{\text{hel}}| < 0.4$, favoring the

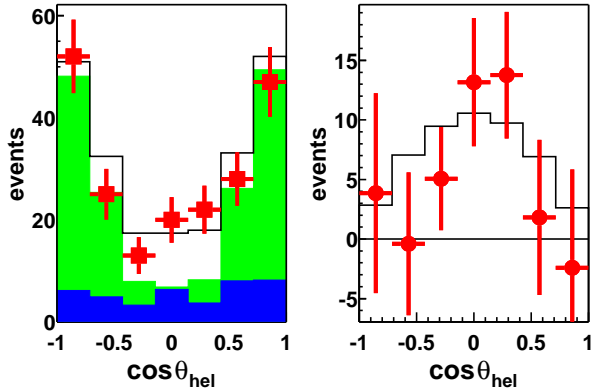


Figure 16. Belle $D^0 \rightarrow \phi\gamma, \phi\pi^0, \phi\eta$ analysis:⁴² cross-check of the $\phi\gamma$ result using the $\cos\theta_{\text{hel}}$ distribution. Left plot: data (points), and MC predictions for the total (open histogram), total background (light), and non- $\phi\pi^0$ background (dark). Right plot: background-subtracted distribution for the data (points) and the MC prediction (histogram).

transversely polarized ϕ of $D^0 \rightarrow \phi\gamma$ over the longitudinally polarized ϕ of the $\phi\pi^0$ and $\phi\eta$ modes. The resulting $\phi\gamma$ invariant mass spectrum shows a clear $D^0 \rightarrow \phi\gamma$ signal of $27.6^{+7.4+0.5}_{-6.5-1.0}$ events (Fig. 15), and is well-described by a linear combinatorial background, the expected $\phi\pi^0$ and $\phi\eta$ contribution, plus the signal. The helicity angle distribution (Fig. 16) is likewise consistent with expectations.

The final results of the analysis are

$$\mathcal{B}(D^0 \rightarrow \phi\pi^0) = (8.01 \pm 0.26 \pm 0.46) \times 10^{-4}$$

$$\mathcal{B}(D^0 \rightarrow \phi\eta) = (1.48 \pm 0.47 \pm 0.09) \times 10^{-4}$$

$$\mathcal{B}(D^0 \rightarrow \phi\gamma) = (2.60^{+0.70+0.15}_{-0.61-0.17}) \times 10^{-5};$$

the $\phi\gamma$ mode is the first radiative decay, and the first FCNC decay, observed in the D meson system. The measured branching fraction is at the upper end of the VMD predictions—consistent with Standard Model expectations—and is in no sense a new physics measurement, but it provides the first experimental reference point for predictions of other FCNC decays.

6. Summary and Prospect

While all observations are still consistent with Standard Model expectations, there has been significant progress in charm analyses sensitive to new physics effects. The D -mixing measurement using $D^0 \rightarrow K^+\pi^-$ is now mature, with a major result released by BaBar, and a Belle analysis in the pipeline; the B -factories will (presumably) exhaust this difficult

technique. The sensitivity to y_{CP} continues to improve, and a 1% measurement is within reach of the current facilities during their projected life. Fitting for CP-violating effects has become standard, and as a robust test for new physics—and a technique still dominated by statistical errors—will become increasingly important in the field. And measurements of the new quantities observable at CLEO-c, and the promising but yet-untried $D^0 \rightarrow K_S^0\pi^+\pi^-$ mixing analysis, are eagerly awaited.

The first flavor-changing neutral current decay in the charm sector, $D^0 \rightarrow \phi\gamma$, has finally been seen, and is consistent with Standard Model expectations due to vector meson dominance. While not the most exciting possible channel— $\gamma\gamma$ or $\mu^+\mu^-$ would have been respectively a shock, and a total revolution in the field—the $\phi\gamma$ observation provides an experimentally-measured point where none previously existed, and will presumably allow more precise SM predictions for other FCNC decays in the future. In the search for other rare and exotic processes, there are continuing improvements in the range of channels studied (with the first $D^0 \rightarrow \gamma\gamma$ limit announced, and the first test of CPT/Lorentz invariance conducted) and the reach of existing analyses (with the $D \rightarrow h\ell\ell$ results from FOCUS). As with mixing, there will be significant contributions to these searches from CLEO-c in the next two years, and we all—including even the charm coordinators at BaBar, Belle, CDF, and FOCUS—are looking forward to new results in this new era.

Acknowledgments

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DISCUSSION

Hal Evans (Columbia): What is the average y_{CP} measurement? Or is there a reason not to calculate it?

Bruce Yabsley: The average would be dominated by preliminary measurements from BaBar and Belle. Further, results appear to be “clumping” based on measurement technique indicating the possibility of systematic problems. That being said, the speaker’s average is $\langle y_{CP} \rangle = (0.9 \pm 0.4)\%$

Further Discussion, Added since LP2003:

It’s appropriate to return to this question in more detail for the written version of the talk. I reserved the y_{CP} average for the Discussion—assuming, correctly, that someone would bring it up—partly for lack of time and partly for lack of a clear idea of how to treat it: any average is dominated by a preliminary number from Belle¹⁷ and results from BaBar which, though “final”, had not been published at the time of the symposium. Since then, BaBar’s paper has appeared in *PRL*,¹⁶ so my reservations are now diminished. The situation, however, is still unclear.

Table 5. Expanded summary of y_{CP} results.

Technique	Experiment	y_{CP} (%)
Fixed target	E791 ¹⁹	$0.8 \pm 2.9 \pm 1.0$
	FOCUS ¹³	$3.4 \pm 1.4 \pm 0.7$
	<i>My average:</i>	2.9 ± 1.4
e^+e^- , untagged	Belle ¹⁴	$-0.5 \pm 1.0 \pm 0.8$
	CLEO ¹⁵	$-1.2 \pm 2.5 \pm 1.4$
	BaBar ¹⁶	$0.2 \pm 0.5^{+0.5}_{-0.4}$
<i>My average:</i>	0.0 ± 0.6	
e^+e^- , D^* -tagged	BaBar, ¹⁶ K^+K^-	$1.5 \pm 0.8 \pm 0.5$
	BaBar, ¹⁶ $\pi^+\pi^-$	$1.7 \pm 1.2^{+1.2}_{-0.6}$
	Belle, ¹⁷ K^+K^-	$1.2 \pm 0.7 \pm 0.4$
<i>My average:</i>	1.4 ± 0.6	
<i>Speaker’s grand average:</i>		0.9 ± 0.4

The results from the various experiments are shown in Table 5, sorted by the type of experiment and the method used: fixed target (E791¹⁹ and FOCUS¹³), e^+e^- with inclusive D^0 samples (Belle,¹⁴ CLEO,¹⁵ and BaBar¹⁶), and e^+e^- with D^* -tagged samples (BaBar¹⁶ and Belle¹⁷). The individual results within the BaBar analysis have been listed sep-

arately for this purpose. There is a clear clustering of the results according to technique: fixed target measures high ($\langle y_{CP} \rangle = 2.9\%$), e^+e^- measures null ($\langle y_{CP} \rangle = 0.0\%$), and the D^* -tagged analyses measure an intermediate value ($\langle y_{CP} \rangle = 1.4\%$). These last results are completely dominant, as can be seen in Fig. 17, where the data are shown in the form of the “ideograms” used by the PDG.¹⁸

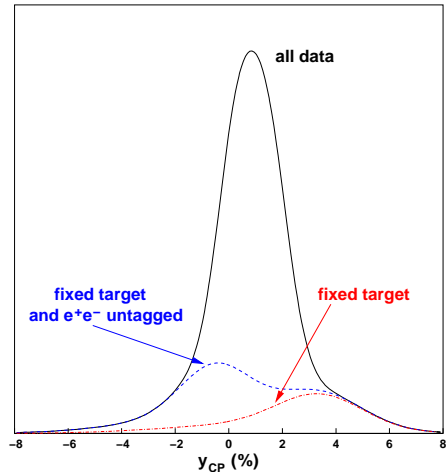


Figure 17. PDG-style “ideogram” of the y_{CP} data in Table 5: each measurement (with mean x_i and total error $\pm \delta x_i$) is represented by a gaussian with central value x_i , error δx_i , and area proportional to $1/\delta x_i$. The sum of all curves (solid), the sum of fixed-target and e^+e^- untagged data (dashed), and the fixed-target data alone (dot-dashed) are shown.

Statistically speaking, the data are consistent, and the average is now 2σ away from zero. But it seems to me a bit worrying that the different techniques don’t actively corroborate each other. Put another way, having first become excited about the (positive) FOCUS result, and then rushed to discount it in the light of (negative) e^+e^- results, I think we should be slow to interpret D^* -tagged results which split the difference.

This question will become urgent after the next round of data-taking at the B -factories, if the central value stays at $y_{CP} \gtrsim 1\%$ as the total error shrinks. One convincing cross-check in this situation would be to analyse D^0 decays to CP-odd final states such as $K_S^0(\rho^0, \omega, \phi)$ and even $K_S^0\eta^{(\prime)}$ at the B -factories: for the same y_{CP} value, the shift in the lifetime has the opposite sign. I know of no such plans at this stage.