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# Charm Physics 1996 – A Retrospective

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A pedagogically oriented review is given of progress made over the past year in our understanding of physics related to the charm quark. Included are discussions of the  $R_c$  deficit, the  $\psi'$  anomaly, charm spectroscopy,  $D$  nonleptonic decays, searches for flavor-changing neutral currents, new limits on  $D^0 - \bar{D}^0$  mixing and prospects for future experimental studies of the charm sector.

## 1. INTRODUCTION

Compared to the publicity given in recent years to the physics of both  $b$ -quarks and  $t$ -quarks, studies of the  $c$ -quark might appear to have become somewhat of a neglected subject. Nonetheless, the year 1996 has been a productive one in the study of charm physics. In the following we provide a personal slice through the corpus of charm-related material. Space limitations do not permit a fully comprehensive review of the subject, and we apologize to those whose work is unmentioned.

## 2. PRODUCING CHARM

In order to study properties of charm hadrons, charm must first be produced. The production occurs via scattering (using hadron, photon and lepton beams) and decay (from the  $Z^0$  boson and  $B$  hadrons).

We begin by reviewing two items which seemed to garner the lion's share of attention to charm physics at this year's conferences. Each involves the creation of  $c\bar{c}$  pairs which then evolve into hadronic final states.

### 2.1. $R_c$ Crisis

The  $R_c$  'crisis' was the concern that the measured ratio  $R_c \equiv \Gamma_{Z^0 \rightarrow c\bar{c}}/\Gamma_{Z^0 \rightarrow \text{hadrons}}$  is smaller than the Standard Model (hereafter SM) value,  $R_c^{\text{SM}} = 0.1725$ . As recently as Moriond '96,<sup>[1]</sup> one had  $R_c^{\text{expt}} = 0.1598(69)$  (a discrepancy of

$-1.8 \sigma$ ), yet by DPF96<sup>[2]</sup> the value had changed to  $R_c^{\text{expt}} = 0.1715(56)$  (a discrepancy of  $-0.1 \sigma$ ).

Thus the  $R_c$  crisis is no more. Together with an enlarged data sample, it was imposition of improved experimental technique which led to the upward revision, including double-tagging procedures and improved verification of closure. Regarding the latter, we mean by 'closure' the assumption that all  $c\bar{c}$  pairs produced at the  $Z^0 \rightarrow c\bar{c}$  vertex ultimately appear as charm hadrons ( $D^0, D^+, D_s^+, \Lambda_c^+, \dots$ ) which then decay weakly. Any correct determination of  $R_c^{\text{expt}}$  must account for all such decay products, and in fact, a careful channel-by-channel analysis of final states such as  $K^-\pi^+$  ( $D^0$ ),  $K^-\pi^+\pi^+$  ( $D^+$ ),  $\phi^0\pi^+$  ( $D_s^+$ ) and  $pK^-\pi^+$  ( $\Lambda_c^+$ ) succeeded in accurately accounting for all decay products from charm. Moreover, a change in the assumed  $D^0 \rightarrow K^-\pi^+$  branching ratio down to its current value also contributed to the rise in  $R_c^{\text{expt}}$ .

### 2.2. $\psi'$ Anomaly at CDF

This refers to the program undertaken by CDF to study  $p\bar{p} \rightarrow \psi'(3686) + X$  at transverse momenta as large as  $p_T = 20$  GeV.<sup>[3],[4]</sup> The history of theoretical attempts to analyze charmonium production follows a somewhat indirect path. The original expectation was that inclusive  $B$  decay ( $B \rightarrow \psi' + X$ ) would give rise to the  $\psi'$  yield. Yet only about 23% could be so identified, the majority having a 'prompt' origin. The leading order (LO) gluon-fusion mechanism ( $gg \rightarrow c\bar{c}[^3S_1] + g$ ) for prompt production predicted  $d\sigma/dp_T$  to be too small and with incor-

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rect  $p_T$  dependence. Although it became appreciated that  $\psi'$  production at large  $p_T$  is dominated by fragmentation of the  $c$ -quark and gluon jets, the normalization for production of color-singlet  $c\bar{c}$  pairs was still too small. Finally, including both color-singlet and color-octet  $c\bar{c}$  pairs<sup>[5]</sup> yielded agreement with the data, although at the cost of fitting certain parameters associated with nonperturbative contributions.<sup>[6]</sup> The fits to  $p\bar{p} \rightarrow \psi' + X$ , however, do not work when applied to  $\gamma p \rightarrow J/\psi + X$ .<sup>[7]</sup>

It is clear that further theoretical and experimental work is yet required. The theory underlying charmonium production is subtle and difficult, and will take some time to sort out. A review of the basics appears in Ref. [8] and other analyses appear regularly.<sup>[9]</sup> Further experimental tests are needed, like that involving the prediction of  $\psi'$  transverse polarization<sup>[10]</sup> associated with the color-octet mechanism.

### 2.3. Additional topics

Charm production is a large subfield of charm physics, and the following four topics are chosen to illustrate the range of activity:

(a) Scattering experiments continue to test the body of QCD predictions for charm hadron production. Thus, Fermilab experiment E769 examined charm production off a nuclear target using  $\pi$ ,  $K$ ,  $\rho$  projectiles.<sup>[11]</sup> The energy dependence for forward production of several types of charm hadrons ( $D^0, \Lambda_c^+, \dots$ ) was found to agree with that predicted by perturbative QCD, and distributions of  $x_F$  and  $p_T^2$  were measured for  $D$ -meson production as a probe of gluon distributions in the target and beam particles.

(b) It is important to have proper theoretical understanding of heavy-quark (*e.g.* charm) contributions to deep inelastic structure functions over the very different kinematical regions  $Q^2 \sim m_c^2$  and  $Q^2 \gg m_c^2$  in order to correctly evolve parton distributions in  $Q^2$  as heavy-quark thresholds are encountered. A recent theoretical analysis is given in Ref. [12].

(c) Work appears on charm production in models of new physics. In the class of examples having two Higgs doublets, flavor-changing couplings exist even at tree level and a decay such as  $t \rightarrow c \gamma$

becomes possible.<sup>[13]</sup>

(d) Finally, attention has been directed over the past several years at the number of  $c$ -quarks produced per  $B$  decay and its possible relation to the discrepancy between theory and experiment regarding the  $B$  semileptonic branching ratio. For a summary given earlier this year, see Ref. [14].

## 3. CHARM HADRON PROPERTIES

From the viewpoint of performing accurate predictions of the SM, the  $c$ -quark mass scale presents a nontrivial challenge. Methods of chiral symmetry are not generally applicable because  $m_c$  is too large, and the use of heavy-quark methodology (which incorporates both heavy-quark effective theory (HQET) and heavy-quark expansions based on the operator product expansion (OPE)) is questionable because  $m_c$  might not be large enough. It will, of course, take more time and effort to decide on the latter point, although the large number of resonances in the charm region (as cited in the 1996 Particle Data Group listing<sup>[15]</sup>) reflects the vigor of QCD dynamical activity and makes problematic the assumption of local duality. The literature, reflecting the lack of a clear winner in the charm region, contains quark models and heavy-quark methods alike, often used in conjunction with additional approaches like lattice-QCD, the  $1/N_c$  expansion and QCD sum rules.

Work continues, however, and there are a number of very active areas involving the physics of charm hadrons. Among these are spectroscopy, weak decays, lifetimes and charmonium studies. In view of space limitations, I defer to the summary on the final item of Ref. [16].

### 3.1. Charm Spectroscopy

Although it may not yet be clear to what extent heavy-quark methods yield reliable quantitative SM predictions in the charm sector, it seems to me beyond doubt that they are already indispensable as an organizing principle. This is nowhere more clear than in charm spectroscopy.

#### 3.1.1. Charm Mesons

A simple example occurs with the  $D$  meson ground-state and first-excited states. Recall some

elementary bookkeeping. For a  $(Q \bar{q})$  meson in which the heavy quark has spin  $\mathbf{s}_Q$  and the light quark has spin  $\mathbf{s}$  and orbital angular momentum  $\ell$ , the meson spin  $\mathbf{S}$  is found via the chain

$$\mathbf{j}_\ell = \mathbf{s} + \ell \implies \mathbf{S} = \mathbf{j}_\ell + \mathbf{s}_Q . \quad (1)$$

The pattern of states thus obtained in the  $D$  system is compiled in Table 1.

Table 1  
Angular momentum coupling for  $Q\bar{q}$ .

$\ell$	0	1	2
$\mathbf{j}_\ell$	1/2	1/2, 3/2	3/2, 5/2
$\mathbf{S}$	0, 1	0, 1, 2	1, 2, 3

There will be transitions between these states, and these are displayed in Figure 1. The selection rules obtained from angular momentum and parity conservation are listed in Table 2.

Table 2  
Angular momentum and parity selection rules.

$D_2^* \rightarrow D$	$D_1 \rightarrow D$	$D_1 \rightarrow D^*$	$D_2^* \rightarrow D^*$
2	—	0, 2	2

The selection rules explain why there is no  $D_1 \rightarrow D$  transition in Figure 1. Invoking heavy-quark symmetry at this point yields an important constraint not covered by the above selection rules, that the  $S$ -wave  $D_1 \rightarrow D^*$  amplitude vanishes, so to leading order all three transition amplitudes are  $D$ -wave. According to Ref. [17], heavy-quark symmetry can reach quantitative agreement with the observed decay rates provided the leading-order predictions are corrected by  $\mathcal{O}(m_c^{-1})$  effects.

### 3.1.2. Charm Baryons

The spin of a  $(Q q_1 q_2)$  baryon having heavy-quark spin  $\mathbf{s}_Q$  and spectator angular momenta  $\mathbf{s}_{12}, \ell$  is constructed as

$$\mathbf{j}_\ell = \mathbf{s}_{12} + \ell \implies \mathbf{J} = \mathbf{j}_\ell + \mathbf{s}_Q \quad (2)$$

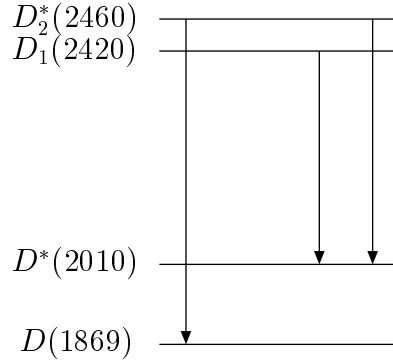


Figure 1.  $D$  meson transitions.

One thus obtains the nine ground state baryons, partitioned into a flavor antitriplet and a flavor sextet, shown in Table 3.

Table 3  
Baryon Ground State

Color	Flavor	$s_{12}$	$J^P$
$\mathbf{3}^*$	$\mathbf{3}^*$	0	$(1/2)^+$ ( $\Lambda_c, \Xi_c$ )
$\mathbf{3}^*$	$\mathbf{6}$	1	$(1/2)^+$ ( $\Sigma_c, \Xi'_c, \Omega_c$ ) $(3/2)^+$ ( $\Sigma_c^*, \Xi_c^*, \Omega_c^*$ )

It is traditional that data on baryon spectroscopy lags somewhat behind that of meson spectroscopy, and such is the case for the charm sector. However, our knowledge of the charm baryon ground state was enhanced in 1996 by contributions from the CLEO collaboration, which cited evidence for  $\Xi_c^{*+}(2645)$ <sup>[18]</sup> and for  $\Sigma^{*++}(2520)$ ,  $\Sigma^{*0}(2518)$ <sup>[19]</sup>. Guided by earlier model calculations<sup>[20]</sup>, each was assigned as a  $S = 3/2$  ground state charm baryon.

If one accepts the CLEO quantum number assignments, this leaves  $\Xi'_c$  and  $\Omega_c^*$  to be discovered. Jenkins used mass sum rules derived from an expansion in  $1/m_c$ ,  $1/N$  and  $SU(3)$  breaking together with input mass values of  $\Lambda_c, \Xi_c, \Sigma_c, \Omega_c, \Sigma_c^*, \Xi_c^*$  to predict  $m_{\Xi'_c} = 2580.8 \pm$

2.1 and  $m_{\Omega_c^*} = 2760.5 \pm 4.9$ .<sup>[21]</sup> Falk, on the other hand, used the evident violation of a sum rule based on heavy-quark and  $SU(3)$  relations,

$$0.84 \simeq \frac{m_{\Sigma_b^*} - m_{\Sigma_b}}{m_{\Sigma_c^*} - m_{\Sigma_c}} = \frac{m_{B^*} - m_B}{m_{D^*} - m_D} \simeq 0.33 \quad , \quad (3)$$

to cast doubt on the the existing  $\Sigma_c$  and  $\Sigma_c^*$  assignments.<sup>[22]</sup> Although it might be the  $\Sigma_b^* - \Sigma_b$  mass difference which causes the problem, the need for direct spin-parity assignments is good to keep in mind. Finally, the subject of mixing between baryons in the flavor **6** and **3\*** multiplets was analyzed in Ref. [23] and in Ref. [24].

### 3.2. Charm Lifetimes

Another area for application of heavy-quark expansions<sup>[25],[26]</sup> is the set of charm lifetimes. At the most elementary level, the decay rate for a heavy hadron  $H_Q$  containing a single heavy quark  $m_Q$  can be expressed as

$$\Gamma(H_Q) = \Gamma_\infty + \Gamma_{\text{non-univ}} \quad . \quad (4)$$

The term  $\Gamma_\infty$  is universal among the set of hadrons  $\{H_Q\}$  and dominates for  $m_Q/\Lambda_{\text{QCD}} \gg 1$ . It is as if the heavy quark were free. The differences in individual  $H_Q$  lifetimes arise in  $\Gamma_{\text{non-univ}}$  from various nonuniversal effects. The display of charm hadron lifetimes in Figure 2, most dramatically the ratio

$$\frac{\tau_{D^+}}{\tau_{\Omega_c^0}} = 16.5 \pm 5.2 \quad , \quad (5)$$

reveals that such terms must play a significant role for charm lifetimes. In the heavy-quark approach, the decay rate is expressed as an expansion in inverse powers of  $m_Q$ ,

$$\Gamma_{H_Q \rightarrow f} = \frac{G_F^2 m_Q^5}{192\pi^3} |\text{KM}|^2 \times \left[ A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \mathcal{O}(m_Q^{-4}) \right] \quad , \quad (6)$$

where  $|\text{KM}|^2$  gives the CKM dependence of the weak decay. Each of the leading  $\{A_n\}$  can be interpreted physically. Thus for charm decay,  $A_2$  contains dependence on (i) the kinetic energy of the  $c$ -quark and (ii) the spin-spin interaction between the  $c$ -quark and the spectators,

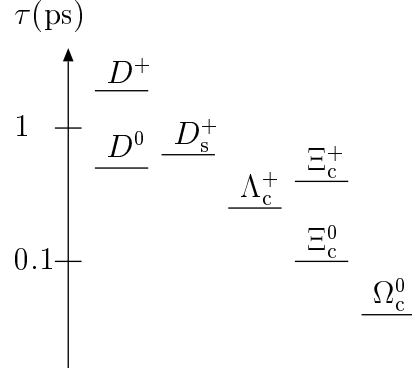


Figure 2. Lifetimes of the charm hadrons.

whereas  $A_3$  includes (iii) weak interaction effects like  $c \rightarrow sud$ ,  $c\bar{q} \rightarrow q_1\bar{q}_2$ ,  $cq \rightarrow q_1q_2$  as well as (iv) a Pauli interference effect which occurs if a spectator quark in the initial state is identical to a quark which appears in a final state in one of the weak transitions of (iii).

Application of this approach to the charm lifetimes is reasonably successful. There appear to be no major disasters, but model dependence remains in estimates of the  $\{A_n\}$ . We recommend the recent summary by Bigi<sup>[27]</sup>.

### 3.3. Leptonic and Semileptonic Decays

The leptonic and semileptonic charm decays are reviewed in Ref. [28]. Charm leptonic decays are important because they determine the decay constants  $f_D$  and  $f_{D_s}$ . There are now several direct measurements of  $f_{D_s}$ , including the recent E653 value  $f_{D_s} = 194 \pm 35 \pm 20 \pm 14$  MeV.<sup>[29]</sup> Lattice-theoretic values of charm decay constants presented at LATTICE96 are similar to those of previous years, *e.g.* the JLQCD collaboration<sup>[30]</sup> cites  $f_D = 202(8)_{-11}^{+24}$  MeV and  $f_{D_s} = 216(6)_{-15}^{+22}$  whereas the MILC collaboration<sup>[31]</sup> has  $f_D = 196(9)(14)(8)$  MeV and  $f_{D_s} = 211(7)(25)(11)$ .

In an interesting contribution to the literature of charm semileptonic transitions, Voloshin argues that large effects are to be expected from Pauli interference of the  $s$ -quark in  $\Xi_c$  and  $\Omega_c$  semileptonic decay, implying sharply enhanced

decay rates relative to  $\Lambda_c$ .<sup>[32]</sup>

### 3.4. Nonleptonic Weak Decays

The data base for nonleptonic decays continues to expand, and a review of the current situation appears in Ref. [14]. As an example, let me cite the recent CLEO analysis of  $D^0 \rightarrow K\bar{K}X$  decays.<sup>[33]</sup> This analysis covers the five final states ( $K^+K^-$ ,  $K^0\bar{K}^0$ ,  $3K_S$ ,  $\pi^0 K_S K_S$ ,  $K^+K^-\pi^0$ ), all of which have branching ratios well under a per cent. Detection of the final two modes represents first observations.

As the study of charm nonleptonic continues, one awaits progress in the two-body final state sector, where many modes such as  $D^+ \rightarrow K^+\eta$  *etc.* remain undetected. Theorists have the most to say about two-body modes and advances of the data set in this area would be welcome.

The theoretical study of charm nonleptonic decays is notoriously difficult, and despite the efforts of many over a number of years there does not exist at present a practical quantitative approach which follows rigorously from first principles. In principle, there seems to be no insurmountable barrier to using lattice-theoretic methods.<sup>[34]</sup> Until such time as lattice studies take over, however, it will be necessary to proceed in a more traditional manner. I shall focus on an interesting contribution which appeared from Buccella, Lusignoli and Pugliese (BLP).<sup>[35]</sup> Their approach incorporates the usual collection of quark diagrams, the latest renormalization group improved weak hamiltonian, and most notably, final-state interaction (FSI hereafter) effects.<sup>[36]</sup> The work is comprehensive and many modes are taken into account. The authors themselves point out some shortcomings, like the assumption of factorization, the use of some as-yet unobserved resonances to generate the FSI and the many free parameters used (in the latest fit, there are 49 data points, 15 parameters, with  $\chi^2 \simeq 70$ ). Not all predictions are successful, such as those for the modes  $D_s^+ \rightarrow \rho^+\eta'$  and  $D^0 \rightarrow K^{*0}\eta$ . As a whole, however, the BLP analysis represents a plausible theoretical laboratory which (one hopes) provides a reasonable picture of the two-body nonleptonic charm decays.

Two recent contributions of the BLP group

are of special interest because both involve as-yet unobserved signals. The first concerns a set of predictions for CP-violating (CPV hereafter) asymmetries.<sup>[37],[35]</sup> We comment on these quantities more fully in Sect. 4.2.4 of this report. It suffices here to note that Ref. [35] cites as the best candidate for detection the asymmetry

$$a_{(\rho\pi)}^{\text{CPV}} \equiv \frac{\Gamma_{D^+ \rightarrow \rho^0 \pi^+} - \Gamma_{D^- \rightarrow \rho^0 \pi^-}}{\Gamma_{D^+ \rightarrow \rho^0 \pi^+} + \Gamma_{D^- \rightarrow \rho^0 \pi^-}} \simeq -2 \times 10^{-3} . \quad (7)$$

More generally, the predicted CPV asymmetries occur at the  $\mathcal{O}(10^{-3})$  level. Another BLP result concerns the difference in decay rates between  $D^0$  and  $\bar{D}^0$ , as obtained from an explicit sum over exclusive modes,

$$\frac{\Delta\Gamma_D}{\Gamma_D} \simeq 2 \frac{\Gamma_{12}^{(D)}}{\Gamma_D} \simeq (1.5 + i 0.0014) \cdot 10^{-3} , \\ \Gamma_{CP=+1} > \Gamma_{CP=-1} .$$

To even attempt such an estimate of  $\Gamma_{12}^{(D)}$ , it is first necessary to have a fairly complete collection of decay amplitudes (magnitudes *and* phases). The small magnitude found for  $\Delta\Gamma_D/\Gamma_D$  is noteworthy because large  $SU(3)$  breaking effects observed in individual decay rates would suggest a rather larger value. On a qualitative level, this reinforces the prediction<sup>[38]</sup> from heavy-quark theory that  $D^0 - \bar{D}^0$  mixing is smaller than that expected from a dispersive approach<sup>[39]</sup> which stresses the large  $SU(3)$  breaking.

## 4. FCNC STUDIES

Due to CKM suppression, the charm sector is not the best of places to seek SM signals associated with flavor-changing neutral current effects. However, this makes charm processes attractive for exploring various new physics effects.<sup>[40]</sup> Below, we first review attempts to detect flavor-changing neutral current decays and then turn to the subject of  $D^0 - \bar{D}^0$  mixing.

### 4.1. FCNC Decays

No flavor-changing neutral current charm decays have yet been observed. We list some upper bounds (at 90% C.L.) announced in 1996:

- E791:[41] Search for  $D^+ \rightarrow \pi^+ \ell^+ \ell^-$   
 $B_{D^+ \rightarrow \pi^+ e^+ e^-} < 6.6 \times 10^{-5}$   
 $B_{D^+ \rightarrow \pi^+ \mu^+ \mu^-} < 1.8 \times 10^{-5}$
- E771:[42] Search for  $D^0 \rightarrow \mu^+ \mu^-$   
 $B_{D^0 \rightarrow \mu^+ \mu^-} < 4.2 \times 10^{-6}$
- CLEO:[43] Search for  $D^0 \rightarrow \ell^+ \ell^-$ ,  $X^0 \ell^+ \ell^-$   
 $B_{D^0 \rightarrow \ell^+ \ell^-}, X^0 \ell^+ \ell^- < \mathcal{O}(10^{-4} \rightarrow 10^{-5})$

Even if a FCNC  $D$ -decay is found, one will need to exercise some caution when interpreting the result. For example, consider the weak radiative transitions  $D \rightarrow M\gamma$  ( $M = \rho, K^*, \text{etc}$ ). The current level of sensitivity is  $B_{D \rightarrow M\gamma} = \mathcal{O}(10^{-4})$ . Now, in the absence of QCD radiative corrections, the associated quark (or short distance) branching ratio is easily calculated to be  $B_{c \rightarrow u\gamma}^{(0)} \simeq 1.4 \times 10^{-17}$ . Although QCD corrections are found<sup>[44],[45]</sup> to increase this value appreciably (*e.g.* Ref. [44] finds  $B_{c \rightarrow u\gamma} \simeq 5 \times 10^{-12}$ ), the effect remains unobservable. It would seem then that observation of  $D \rightarrow M\gamma$  would signal the presence of new physics. However, there are still long range effects to be considered. Several such analyses for  $B_{D \rightarrow M\gamma}$  have been carried out in terms of vector dominance<sup>[44]</sup> and weak annihilation<sup>[47]</sup> mechanisms, with the result  $\implies B_{D \rightarrow M\gamma} = \mathcal{O}(10^{-6})$ . See also Ref. [46] The lesson is that misinterpretation of FCNC signals is a real possibility unless long range effects are first understood.<sup>[40]</sup>

## 4.2. Mixing

Of the recent occurrences involving charm, some of the most interesting have concerned  $D^0 - \bar{D}^0$  mixing. We first give a brief review of the subject and then consider recent theoretical and experimental developments.

### 4.2.1. Basics of $D^0 - \bar{D}^0$ mixing

A glance at Figure 3 reminds us of the key features of this subject. Neither a difference in mass  $\Delta m_D$  nor a difference in rate  $\Delta\Gamma_D$  has yet been observed,

$$|\Delta m_D| < 1.3 \times 10^{-13} \text{ GeV} ,$$

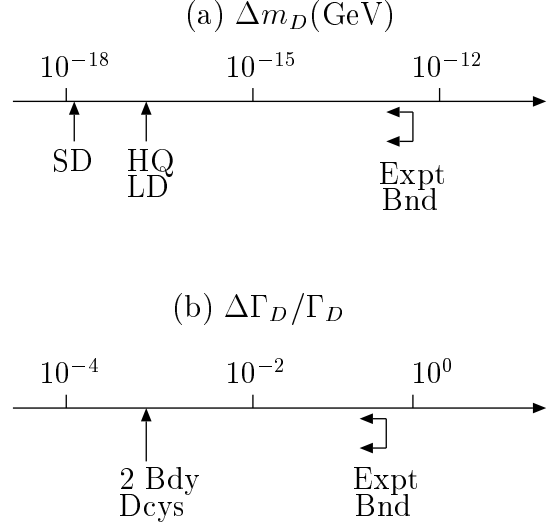


Figure 3. Current status of  $D^0 - \bar{D}^0$  mixing: (a)  $\Delta m_D$  in units of GeV, (b)  $\Delta\Gamma_D/\Gamma_D$ .

$$|\Delta\Gamma_D| < 2.7 \times 10^{-13} \text{ GeV} . \quad (8)$$

An equivalent set of quantities often more useful for direct comparison of theory with experiment, together with their bounds is

$$\begin{aligned} x_D &\equiv \frac{|\Delta m_D|}{\Gamma_D} < 0.088 , \\ y_D &\equiv \frac{|\Delta\Gamma_D|}{2\Gamma_D} < 0.085 , \end{aligned} \quad (9)$$

as well as the parameter

$$r_f \equiv \frac{B_{D^0 \rightarrow \bar{D}^0 \rightarrow \bar{f}}}{B_{D^0 \rightarrow f}} . \quad (10)$$

To get some feeling for the difficulty in detecting  $D^0 - \bar{D}^0$  mixing, we compare the situation for mixing in the  $B_d$  system (Figure 4) with that in the  $D$  system (Figure 5). In these figures we plot the imaginary parts of the Breit-Wigner profile for each particle. Thus, in Figure 4 the separation of the two peaks gives  $\Delta m_{B_d}$  and since the SM expectation is that  $\Delta m_{B_d} \gg \Delta\Gamma_{B_d}$  the peaks have the same widths. An analogous depiction for the  $D$  system is given in Figure 5 except it appears that one of the peaks has been forgotten.

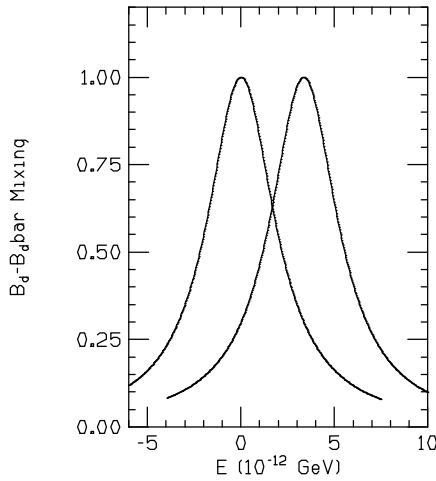


Figure 4. Profile of  $B_d - \bar{B}_d$  mixing.

However, there actually are two peaks but they are so closely spaced that in a graph where the decay width has a reasonable proportion, it is not possible to distinguish the  $D^0$  and  $\bar{D}^0$  profiles. For an instructive comparison of all four meson mixings, see Ref. [48].

#### 4.2.2. Theoretical aspects of $D^0 - \bar{D}^0$ mixing

There exist various theoretical estimates of  $|\Delta m_D|$ , which in Figure 5 we have partitioned into two broad categories, short-distance (SD) and heavy-quark/long-distance (HQ and LD). The SD estimate arises from the box diagram at the quark level,<sup>[49],[39]</sup>

$$|\Delta m_D^{\text{box}}| \simeq 5 \times 10^{-18} \text{ GeV} . \quad (11)$$

The heavy-quark<sup>[38]</sup> and long-distance<sup>[39]</sup> contributions are larger in magnitude. Although the difference between these latter values might be of some theoretical interest, the really important point for us is that each is far below the current experimental limit. With this observation, we are ready to consider a recent flurry of activity on the topic of time dependence in  $D^0 - \bar{D}^0$  nonleptonic mixing amplitudes.

For  $x_D, y_D \ll 1$  and  $|\lambda| \ll 1$  ( $\lambda$  is defined below), the time-dependent decay rate for the tran-

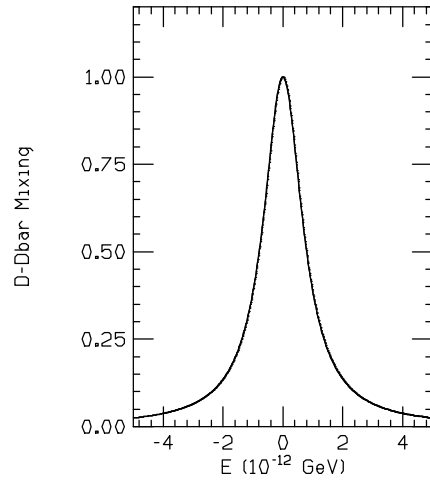


Figure 5. Profile of  $D - \bar{D}$  mixing.

sition of  $D^0$  to some final state  $f$  time can be written as<sup>[62],[50]</sup>

$$\Gamma_{D^0(t) \rightarrow f} \propto e^{-\Gamma_D t} \left[ X + Y t + Z t^2 \right] . \quad (12)$$

The constant term  $X = 4|\lambda|^2$  arises from doubly-suppressed Cabibbo decay (DCSD). It mimics the mixing signal and is present even in the absence of mixing. The quadratic term  $Z$  is entirely due to mixing,

$$Z \equiv (\Delta m_D)^2 + \left( \frac{\Delta \Gamma_D}{2} \right)^2 . \quad (13)$$

The linear term  $Y$  arises from interference and can be written as

$$Y = 2\mathcal{R}e \lambda \Delta \Gamma_D + 4\mathcal{I}m \lambda \Delta m_D , \quad (14)$$

where  $\lambda$  is a complex number defined by

$$\lambda \equiv \frac{p}{q} \frac{A}{B} , \quad (15)$$

with  $p$  and  $q$  being the usual mass matrix parameters and

$$A \equiv \langle f | H_{\text{wk}} | D^0 \rangle , \quad B \equiv \langle f | H_{\text{wk}} | \bar{D}^0 \rangle . \quad (16)$$

Authors have tended to argue that the  $\Delta \Gamma_D$  contribution to the  $Y$  term is negligible. The remaining contribution to  $Y$  is proportional to  $\mathcal{I}m \lambda$ ,



which can be nonzero if (i) CPV is present (thus inducing a phase in  $p/q$ ) and/or (ii) the FSI are different in  $D^0 \rightarrow f$  and  $\bar{D}^0 \rightarrow f$  (thus inducing a phase in  $A/B$ ).

Two papers appeared in 1995 each pointing out the potential importance of the  $Y$ -term for studies of mixing in the  $D$  sector. Wolfenstein argued that detection of mixing at current levels of sensitivity would require new physics, and that in the absence of FSI, the effect would involve CPV.<sup>[51]</sup> Blaylock *et al* performed a careful analysis of the time dependence in mixing and discussed the importance of allowing for FSI effects in any model-independent experimental analysis.<sup>[50]</sup> More recently, Browder and Pakvasa provided a more detailed look at new physics possibilities.<sup>[52]</sup> They also stressed that the term  $Y$  would survive (i) for zero CPV in the combination  $\Gamma_{D^0(t)+\bar{D}^0(t)}$  and (ii) for zero FSI in the combination  $\Gamma_{D^0(t)-\bar{D}^0(t)}$ . CPV contributions to  $D^0 - \bar{D}^0$  mixing from a variety of new physics scenarios are summarized in Ref. [53] and in Ref. [54].

#### 4.2.3. Results of E791

A number of results from the Fermilab experiment E791 appeared during the past year. This experiment recorded  $2 \times 10^{10}$  raw events from 500 GeV/c  $\pi^-$  interactions, and the ultimate yield of about  $2 \times 10^5$  reconstructed charm is the largest sample to date. No signal for  $D^0 - \bar{D}^0$  mixing was found by E791. In the following we list some specific results, beginning in Table 4 with a bound on mixing obtained from semileptonic decay<sup>[55]</sup> and including for comparison the earlier E615 result.

Table 4  
Mixing limits at 90% C.L. (semileptonic).

Experiment	E615	E791
$r_{K\ell\nu}^{\text{mix}}$	$< 0.56 \%$	$< 0.50 \%$

Upon assuming zero mixing in its nonleptonic data sample, E791 obtained<sup>[56]</sup> a DCSD signal in the  $K\pi$  mode comparable to the wrong-sign signal obtained earlier by CLEO, as shown in Ta-

ble 5.

Table 5  
DCSD (assuming  $r_D^{\text{mix}} = 0$ ).

Experiment	$r_D^{\text{DCSD}}$
CLEO	$(0.77 \pm 0.25 \pm 0.25) \%$
E791	$(0.68^{+0.34}_{-0.33} \pm 0.07) \%$

Finally, Table 6 displays the mixing values obtained from nonleptonic decays ( $D \rightarrow K\pi$  and  $D \rightarrow K3\pi$ ) and obtained under the most general of conditions, *i.e.* making no assumptions regarding the absence of CPV. The 90% C.L. upper bounds are  $r_{K\pi, K3\pi}^{\text{mix}}(\bar{D}^0 \rightarrow D^0) < 0.74\%$  and  $r_{K\pi, K3\pi}^{\text{mix}}(D^0 \rightarrow \bar{D}^0) < 1.45\%$ .

Table 6  
Mixing signals (nonleptonic).

Mixing	$r_{K\pi, K3\pi}^{\text{mix}}$
$\bar{D}^0 \rightarrow D^0$	$(0.18^{+0.43}_{-0.39} \pm 0.17) \%$
$D^0 \rightarrow \bar{D}^0$	$(0.70^{+0.58}_{-0.53} \pm 0.18) \%$

The reader might wonder, despite the large number of events that E791 generated, why its bounds are not even lower. It is important to keep in mind that E791 was a hadroproduction fixed-target experiment. In this setting, virtually all charm particles produced were highly energetic ( $p_D \geq 20$  GeV) and forwardly directed ( $\theta \leq 20$  mr) with a large multiplicity of charged particles ( $n_{\text{ch}} \gg 1$ ). This presents a difficult environment for extracting a clean mixing signal.

#### 4.2.4. Bounds on CP violation

Lastly, we report on the E791 search for CPV in charged  $D$  decays.<sup>[57]</sup> Studies of CPV can be divided into two categories, indirect or direct.<sup>[58]</sup> The former consists of mixing-induced CPV and occurs only for neutral mesons. It is the latter we consider here, for which FSI constitute a necessary ingredient. Because the  $c$ -quark mass scale is still in the resonance region, FSI are clearly

present and presumably large. One defines a CPV asymmetry associated with decays to a final state  $f$  and its conjugate  $\bar{f}$  as

$$a_f^{\text{CPV}} \equiv \frac{\Gamma_{D \rightarrow f} - \Gamma_{\bar{D} \rightarrow \bar{f}}}{\Gamma_{D \rightarrow f} + \Gamma_{\bar{D} \rightarrow \bar{f}}} . \quad (17)$$

The E791 results are compiled in Table 7.

Table 7  
CPV asymmetries in  $D^\pm$  decay.

Mode ( $f$ )	Asymmetry
$K^- K^+ \pi^+$	$-0.014 \pm 0.029$
$\phi \pi^+$	$-0.028 \pm 0.036$
$\bar{K}^{*0}(892) K^+$	$-0.010 \pm 0.050$
$\pi^- \pi^+ \pi^+$	$-0.017 \pm 0.042$

Statistical errors in the first three modes in Table 7 are more than two times smaller than in previous experiments, and the final mode represents a new measurement. It is apparent that the level of experimental uncertainty is still an order of magnitude larger than the predicted  $\mathcal{O}(10^{-3})$  SM effects described earlier in Sect. 3.2.

## 5. FUTURE CHARM STUDIES

Experimental advances will continue in the near term, such as completion of the E791 data analysis, the forthcoming Fermilab experiments 831 and 835, ongoing CLEO measurements, *etc.* Let us consider some longer term prospects.

### 5.1. Tau-charm factory

This topic is covered by the next speaker<sup>[59]</sup> in these proceedings. The reader should also consult the incisive summary of  $D$  physics possibilities at a  $\tau c F$  by the Orsay group.<sup>[60]</sup> A facility running at  $\psi(3770)$  and  $\psi(4160)$  will produce *coherent*  $P$ -wave  $D^0 \bar{D}^0$  pairs. There already exists an abundant literature on this interesting quantum mechanical system, starting with the original Bigi-Sanda analysis<sup>[61]</sup>, including Liu's preprint<sup>[62]</sup> and continuing up to the thorough exposition of Xing.<sup>[63]</sup>

### 5.2. Asymmetric B-factory

Although the main objective of  $B$ -factory physics is detection of CPV in the  $b$ -quark sector, one should keep in mind the potential for doing  $c$ -quark studies as well. For example, a  $D^0 - \bar{D}^0$  mixing search could entail running at  $\Psi(4S)$ , using  $D \rightarrow K\pi\pi$  as a tag and employing the semileptonic decay  $D^0 \rightarrow K\ell\nu$  to probe mixing. It has been estimated that for a machine luminosity of  $\mathcal{L} \simeq 3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  and a run time of  $10^7$  s. would yield roughly  $5 \times 10^4$   $D$ 's per year.<sup>[64]</sup> Utilizing the semileptonic mode would present a relatively clean environment for detection.

### 5.3. Hadroproduction

There is potential for doing a hadroproduction experiment with an even larger sample than E791. As with E791, one could use a  $D^* \rightarrow D\pi_{\text{soft}}$  tag, and there would be the usual hadroproduction background problems.

In relation to a new interaction point ('C0') under construction at Fermilab, an Expression of Interest has been filed by the CHARM2000 collaboration for the purpose of studying a variety of charm physics items (CPV, FCNC,  $L=1$  charm mesons, *etc.*). A wire target would be inserted in the beam halo, and with a spectrometer of relatively modest cost and existing detector/trigger/data-acquisition technologies, it is anticipated that a high statistics, high impact experiment could be run in either collider or fixed target mode. For example, assuming a run of  $10^7$ s with an interaction rate of  $10^6$  int/s, a charm cross section of the form

$$\frac{\sigma_{D^0 + \bar{D}^0}}{\sigma_{\text{inel}}} \simeq (6.5 \pm 1.1) \times 10^{-4} A^{0.29} , \quad (18)$$

an acceptance-times-efficiency of  $(10 \pm 3)\%$  for the proposed detection conditions and  $B_{D \rightarrow K\pi} \simeq 0.05$ , one calculates

$$\begin{aligned} n_{D \rightarrow K\pi} &= \\ &= 10^7 \text{ s} \cdot 10^6 \frac{\text{int}}{\text{s}} \cdot 6.5 \times 10^{-4} A^{0.29} \cdot 0.1 \cdot 0.04 \\ &\simeq 2.6 \times 10^7 A^{0.29} \\ &\simeq 10^8 . \end{aligned}$$

The charm yield of  $n_D \simeq 10^8/\text{yr}$  for reconstructed  $D \rightarrow K\pi$  would be substantial. At this level of

statistics, searches for CPT-violation might become meaningful.<sup>[65]</sup>

#### 5.4. HERA

One should not ignore the potential at HERA for making contributions to charm studies. Measured  $eP$  charm-production cross sections together with an integrated luminosity of  $250 \text{ pb}^{-1}$  implies a yield of  $c\bar{c}$  pairs in excess of  $10^8$ . For a detailed study, see Ref. [66] as well as the recent summaries of Ref. [67].

### 6. CONCLUDING REMARKS

The charm sector of the Standard Model proved to be a fruitful area for study in 1996, while leaving lots yet to be done. The everpresent need for data will continue to be met by experimentalists, next year and beyond. Theorists will continue to use charm hadrons for probing QCD dynamics (while awaiting the ultimate ascendancy of lattice-QCD studies) and will also extend the catalog of new physics signals.

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