Charm2000: A $>10^8$-charm experiment for the turn of the millennium

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I discuss the physics reach of a fixed-target charm experiment which can reconstruct $>10^8$ charm decays, three orders of magnitude beyond the largest extant sample. Such an experiment may run at Fermilab shortly after the Year 2000. In addition to “programmatic” charm physics such as spectroscopy, lifetimes, and tests of QCD, this “Charm2000” experiment will have significant sensitivity to new physics in the areas of $CP$ violation, flavor-changing neutral-current and lepton-number-violating decays, and mixing, and could observe direct $CP$ violation in Cabibbo-suppressed decays at the level predicted by the Standard Model.

1. Introduction

Charm experiments have made important contributions to our effort to test the Standard Model and search beyond it. I discuss in this paper the prospects for increased contributions in the years ahead, and I argue for a new fixed-target experiment to exploit to the full the demonstrated ability of the Fermilab Tevatron to produce very large samples of charm decays which can be reconstructed with small background.

Following the more-or-less simultaneous discovery of the charm quark in fixed-target $e^+e^-$ and $e^+e^-$ collisions, for many years experiments at $e^+e^-$ colliders dominated the study of charmed particles. Starting in $\approx 1985$, silicon vertex detectors made fixed-target experiments once again competitive. More recently, advances in data acquisition bandwidth and offline computing power have allowed the recording of the very large unbiased event samples of Fermilab E769 and E791. In parallel with the development of higher-intensity photon beams, these developments have allowed exponential growth in the sensitivity of fixed-target charm experiments, as illustrated in Fig. 1. Current charm samples are in the $10^5$-reconstructed-decays range, the Fermilab hadroproduction experiment E791 having the largest sample at $\approx 250,000$ events. Fermilab experiments E831 and E781 aim to reach the $10^6$-event level in the 1996/7 Fermilab fixed-target run.

![Figure 1. Yield of reconstructed charm vs. year of run for completed or approved Fermilab fixed-target charm experiments with the highest statistics for their generation; symbols indicate type of beam employed.](image)

At the CHARM2000 Workshop the prospect of pushing to substantially higher sensitivity was
considered. A sample of $>10^8$ events was identified as a desirable goal for a next-generation experiment. Such sensitivity could bring within reach the observation of $CP$ violation in charm decay at the level expected in the Standard Model, while extending sensitivity to new physics by two orders of magnitude in statistical power. As described below, such an advance appears feasible in an experiment to run in the Year $\approx 2000$.

2. High-Impact Charm Physics

“High-impact” denotes measurements which are particularly sensitive to new, non-Standard-Model physics. The Standard Model (SM) contains two key mysteries: the origin of mass and the existence of multiple fermion generations. While the former mystery may be resolved by the LHC, the latter appears to originate at higher mass scales, which can only be studied indirectly. Such effects as $CP$ violation, mixing, and flavor-changing neutral or lepton-number-violating currents may hold the key to physics at these new scales. Because in the charm sector the SM contributions to these effects are small, these are areas in which charm studies can provide unique information. In contrast, in the $s$- and $b$-quark sectors in which such studies are typically pursued, there are large SM contributions to mixing and $CP$ violation, which for new-physics searches constitute backgrounds.

Table 1 summarizes current sensitivities in high-impact charm physics. Also indicated is the sensitivity achievable in Charm2000, based on LHC yields estimates such as those in Table 2. No other proposed experiment is competitive in reach.

I next discuss each physics topic in more detail, then summarize the salient aspects of the Charm2000 experiment.

2.1. Direct $CP$ violation

The Standard Model predicts direct $CP$ violation at the $\sim 10^{-3}$ level in singly-Cabibbo-suppressed decays (SCSD) of charm $D^0 \to \pi^-\nu$, $D^+ \to K^-\pi^+\pi^-$, and other $CP$-violating $D$ decays. Asymmetries in all three categories could reach $\sim 10^{-2}$ in such scenarios as non-minimal supersymmetry and in left-right-symmetric models. There are also expected SM asymmetries of $\approx 3.3 \times 10^{-3}$ ($= 2\times 10^{-3}$) due to $K^0$ mixing in such modes as $D^+ \to K_S\pi^+$ and $K_S\ell\nu$, which should be observed in Charm2000 or even in predecessor experiments. While $K^0$-induced $CP$ asymmetries might teach us little we don’t already know, they will at least constitute a calibration for the experimental systematics of asymmetries at the $10^{-3}$ level. However, Bigi has pointed out that a small new-physics contribution to the DCSD rate could amplify these asymmetries to $O(10^{-2})$.

The signal for direct $CP$ violation is an absolute rate difference between decays of particle and antiparticle to charge-conjugate final states $f$ and $\bar{f}$:

$$A = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}. \quad (1)$$

Extrapolation from sensitivity in E687 implies $CP$ sensitivities in Charm2000 in SCSD modes of $\approx 10^{-3}$ at 90% confidence. Because of the $D\bar{D}$ production asymmetry, in fixed-target experiments the rates in Eq. 1 are in practice normalized to the observed rates in Cabibbo-favored modes. The ratiometric nature of the measurement reduces sensitivity to systematic biases, but at the $10^{-3}$ level systematics will need to be studied carefully.

Since one CFD mode must be used for normalization, the search for direct $CP$ violation in CFD modes is actually a search for $CP$-asymmetry differences among various modes. Given the differing final-state interactions, if new physics causes $CP$ violation in CFD modes, such differences are not unlikely. The yields indicated in Table 2 imply $CP$ sensitivity at the few $\times 10^{-4}$ level in Charm2000 for $D^0 \to K^-\pi^+\pi^-\pi^+$, normalized to the production asymmetry observed in $D^0 \to K^-\pi^+$. For DCSD modes, extrapolations from preliminary E791 results on $D^+ \to K^+\pi^+\pi^-$ and CLEO’s observation of $D^0 \to K^+\pi^-$ to $K^+\pi^\pm$, here and elsewhere in this paper charge-conjugate states are generally implied even when not stated.
The few improvements in vertex resolution and particle extrapolations are conservative and ignore expected effects. Detailed simulations are underway to assess these effects.

SM predictions for direct CP violation are rather uncertain, since they require assumptions for final-state phase shifts as well as CKM matrix elements. The predictions given in Table 1 are representative, but the theoretical uncertainties are probably larger than indicated there. However, given the order of magnitude expected in charm decay, the Charm2000 experiment might make the first observation of direct CP violation outside the strange sector, or indeed the first observation anywhere if (as may well be the case) signals prove too small for detection in the next round of experiments (21,22). They can proceed via loops at rates which are predicted to be unobservably small, e.g. for $D^0 \rightarrow \mu^+\mu^-$ (which suffers also from helicity suppression in the SM) the predicted branching ratio is $\sim 10^{-19}$ (23,24), and for $D^+ \rightarrow \pi^+\mu^+\mu^-$ it is $\sim 10^{-10}$ (23,24).

Long-distance effects increase these predictions by some orders of magnitude, but they remain of order $10^{-15}$ to $10^{-13}$ (23,51). Various extensions of the SM (29,33) predict effects substantially larger than this, for example in models with a fourth generation, both $B(D^+ \rightarrow \pi^+\mu^+\mu^-)$ and $B(D^0 \rightarrow \mu^+\mu^-)$ can be as large as $10^{-9}$ (29). Experimental sensitivities are now in the range $\sim 10^{-4}$ to $10^{-5}$ (33,35) and are expected to reach $\sim 10^{-5}$ to $10^{-6}$ in E831 (38).

While Charm2000 aims at a single-event branching-ratio sensitivity of $\sim 10^{-9}$, FCNC limits are typically background-limited, so sensitivities can be expected to improve as the square root of the number of events reconstructed. In some cases, however, more dramatic improvement may result from improved lepton identification. For $D^+ \rightarrow \pi^+\mu^+\mu^-$, scaling E791 sensitivity (33) by a factor of $\sqrt{2000}$ gives few $\times 10^{-7}$ sensitivity in Charm2000. This estimate may be conservative, since the simple muon detection scheme employed by E791 (one layer of scintillation counters following 2.5 m of steel equivalent) resulted in a (momentum-dependent) $\pi^\pm\mu^-$ misidentification probability ranging from 4.5 to 20% (33), and it should be possible to reduce this to $\approx 1\%$ in Charm2000. With modern calorimetry for electron identification one expects to do almost as well for $\pi ee$ as for $\pi\mu\mu$. For $D^0 \rightarrow \mu^+\mu^-$ and $e^+e^-$, extrapolation from WA92 (33) implies sensitivity of $10^{-7}$ per mode.

### 2.3. Lepton-Number-Violating Decays

There are two lepton-number-violating effects which can be sought: decays violating conservation of lepton number (LNV) and decays violating conservation of lepton-family number (LFNV). LFNV decays (such as $D^0 \rightarrow \mu^+\mu^-$) are expected in theories with leptoquarks (32), heavy neutrinos (3), extended technicolor (39), etc. LNV decays (such as $D^+ \rightarrow K^-\pi^+\pi^+$ or $\Sigma^+\pi^+\pi^-$) can arise in GUTs and have been postulated to play a role in the development of the baryon asymmetry of the Universe (40). Since no known fundamental principle forbids either type of decay, it is of interest to search for them as sensitively as possible.

Although much smaller decay widths can be probed in $K$ decays, there are simple theoretical arguments why LFNV charm decays are nevertheless worth seeking. For example, if these effects arise through Higgs exchange, whose couplings are proportional to mass, they will couple more strongly to charm than to strangeness (41). Furthermore, LFNV currents may couple to up-type quarks more strongly than to down-type (32,42).

As shown in Table 1, the best existing limits come in most cases from the $e^+e^-$ experiments Mark II, ARGUS, and CLEO (although the hadroproduction experiment Fermilab E653 dominates in modes with same-sign dimuons) and are typically at the $10^{-3}-10^{-4}$ level (36,37). E831 expects to lower these limits to $\sim 10^{-6}$ (38), and Charm2000 should reach $\sim 10^{-7}$. 

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#### Footnotes

1. $K^+\pi^-$ (19) suggest CP sensitivity in Charm2000 at the few $\times 10^{-3}$ to $\approx 10^{-2}$ level (10). These extrapolations are conservative and ignore expected improvements in vertex resolution and particle identification.

2. SM predictions for direct CP violation are rather uncertain, since they require assumptions for final-state phase shifts as well as CKM matrix elements (13,14). The predictions given in Table 1 are representative, but the theoretical uncertainties are probably larger than indicated there (20).

3. Here $\pi^0$ is of interest to search for them as sensitively as possible.

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2.4. Mixing and Indirect CP Violation

$D^0\bar{D}^0$ mixing may be one of the more promising places to look for low-energy manifestations of physics beyond the Standard Model. SM contributions to $|\Delta M_D|$ are estimated $\lesssim 10^{-2}$ to give

$$r_{\text{mix}} \sim (\Delta M_D/\Gamma_D)^2 < 10^{-8};$$

any observation at a substantially higher level will be clear evidence of new physics. Many nonstandard models predict much larger effects. An interesting example is the multiple-Higgs-doublet model recently expounded by Hall and Weinberg [45], in which technicolor [39], leptoquarks [32], left-right symmetry [46] and DCSD and peak at 1 lifetime due to the factor $t^4$; and the third and fourth terms reflect interference between mixing and DCSD and so give significantly better sensitivity. At present levels of sensitivity, allowing an arbitrary interference phase when fitting decay-time distributions reduces the stringency of the resulting limit [58,59].

Extrapolation by $\sqrt{\text{Charm2000}}$ from preliminary E791 results [59] suggests sensitivity of $\approx 2 \times 10^{-5}$ in Charm2000 (neglecting interference), which with improvements in particle identification and resolution for the tagging pion might approach $10^{-5}$. Since the interference term is linear in $\Delta M_D$ while the mixing term is quadratic, the ratio of the interference and mixing contributions goes as $1/\Delta M_D$. Thus as experimental sensitivity improves and smaller and smaller values of $\Delta M_D$ are probed, interference becomes relatively more important. In a (model-dependent) estimate of Charm2000 sensitivity based on the prescription of Browder and Pakvasa [55], the interference term improves sensitivity slightly, and $10^{-5}$ sensitivity is obtained [10].

Semileptonic decays offer a way to study mixing free from the effects of DCSD. A preliminary result from E791 using $D^\ast$-tagged $D^0 \to K^\pm \pi^\mp$ events indicates sensitivity at the $\approx 0.5\%$ level [60]. Extrapolation by $\sqrt{\text{Charm2000}}$ suggests $10^{-4}$ sensitivity in Charm2000, but use of muonic decays as well, plus improvements in lepton identification and resolution for the tagging pion, may give significantly better sensitivity. At the CHARM2000 Workshop, Morrison suggested $10^{-5}$ sensitivity may be possible [11].

Liu has stressed the importance of setting limits on $\Delta \Gamma$ as well as on $\Delta M$. Although typical extensions of the SM which predict large $\Delta M$ also predict $\Delta \Gamma \gg \Delta \Gamma$, from an experimentalist’s viewpoint both should be measured if possible. This can be done quite straightforwardly by comparing the lifetime measured for

The experimental situation regarding $D^0\bar{D}^0$ mixing is complicated by the presence of DCSD.

Since both effects can lead to the same final states, one needs to distinguish them using time-resolved measurements [1]. In the notation of Refs. [53] and [55], the time dependence for wrong-sign decay is given by

$$\Gamma(D^0(t) \to K^\pm \pi^\mp) = |B|^2 \left[ \frac{4}{\Gamma_D^2} \Delta \Gamma \right] \times e^{-\Gamma_D t} \left\{ (4|\lambda|^2 + (\Delta M^2 + \Delta \Gamma^2/4)t^2 + 2\text{ Re}(\lambda) \Delta \Gamma t + 4\text{ Im}(\lambda) \Delta M t^4) \right\},

\text{ and there is a similar expression for } \bar{D}^0 \to K^- \pi^+ \text{ in which } \lambda \text{ is replaced by } \bar{\lambda}. \text{ In Eq. 2 the first term on the right-hand side is the DCSD contribution, which peaks at } t = 0; \text{ the second is the mixing contribution, which peaks at } 2 D^0 \text{ lifetimes because of the factor } t^2; \text{ and the third and fourth terms reflect interference between mixing and DCSD and so give significantly better sensitivity. At present levels of sensitivity, allowing an arbitrary interference phase when fitting decay-time distributions reduces the stringency of the resulting limit [58,59].}

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CP-even modes (such as \(K^+K^-, \pi^+\pi^-\)) with that for CP-odd modes or (more simply) with modes of mixed CP (such as \(K^-\pi^+\)). Liu has estimated the Charm2000 sensitivity at \(\sim 10^{-5} - 10^{-6}\) in \(g^2 \equiv (\Delta \Gamma/2\Gamma)^2\) \([77]\).

### 2.4.1. Indirect CP violation

In the SM \(D^0\bar{D}^0\) mixing is negligible, and any indirect CP-violating asymmetries are expected to be less than \(10^{-4}\) \([14]\). However, possible mixing signals at the \(\approx 1\%\) level have been reported \([19, 2]\). Given the E691 mixing limit these presumably represent enhanced DCSD signals. If a significant portion of this rate is mixing, new physics must be responsible \([13, 50]\). Indirect CP violation at the \(\lesssim 1\%\) level is then possible \([6, 8, 2, 5, 66]\).

Several authors have suggested that the CP-violating signal, which arises from the interference term of Eq. 2, may be easier to detect than the mixing itself \([3, 4]\). In particular, Browder and Pakvasa \([55]\) point out that in the difference \(\Gamma(D^0 \rightarrow K^+\pi^-) - \Gamma(D^0 \rightarrow K^-\pi^+)\), the DCSD and mixing components cancel, leaving only the fourth term of Eq. 2. Thus if indirect CP violation is appreciable, this is a particularly clear way to isolate the interference term.

### 3. Testing the Standard Model with Charm

In addition to searches for effects due to new physics, high-sensitivity charm measurements address a variety of Standard-Model issues. These have been discussed recently by Sokoloff \([64]\), Sokoloff and Kaplan \([6]\), and Wiss \([3]\).

#### 3.1. Testing the heavy-quark effective theory

Heavy-quark symmetry can be used to predict many nonperturbative properties of hadrons containing a heavy quark (including form factors as discussed below). As a rigorous limit of QCD, HQET needs to be tested in its own right, but it is also important as a method for extracting \(V_{ub}\) and \(V_{cb}\) from \(B\)-decay measurements. HQET can be tested in the charm sector through its predictions \([12, 13, 14, 56]\) for the masses and widths of the orbitally-excited \(D^{*}\) mesons \([8]\). Charm2000 should achieve few-percent fractional errors on the masses and widths of many \(D^{*}\) states, where present measurements are at the \(\approx 50\%\) level \([58, 58, 71]\). By probing the importance of finite-mass effects at the charm-quark mass, such measurements will help establish to what extent HQET is applicable to beauty \([7]\).

### 3.2. Semileptonic form factors

Semileptonic form factors are a testing ground for nonperturbative QCD effects \(\[3\]\). They are also important for extraction of CKM matrix elements from charm decay and for CP-violation studies in beauty decay. For example, the method proposed by Dunietz \([72]\) for measuring the unitarity-triangle angle \(\gamma\) using branching ratios for \(B_d \rightarrow K^*\psi\) and \(\rho^0\psi\) requires knowledge of semileptonic form factors and helicity amplitudes. These should be the same in \(D\) as in \(B\) decay, thus precise measurements in the charm sector will be an important input. Modeling the \(D^+ \rightarrow K^{*0}\ell\nu\) and \(\rho^0\ell\nu\) form factors with single-pole forms, the pole mass should be measurable in Charm2000 to better than \(1\%\). The polarization of the \(K^*\) (the ratio of longitudinal to transverse form-factors) should be measurable with \(\approx\)percent statistical and systematic uncertainties, and that of the \(\rho^0\) with few-percent statistical accuracy. \(D_S \rightarrow \phi\ell\nu\) should be measured with similar precision, providing another test of heavy-quark symmetry \([7]\).

### 3.3. Studying the CKM matrix with semileptonic decays

Semileptonic decays can be used to measure the CKM-matrix elements \(V_{cs}\) and \(V_{cd}\). Currently, \(|V_{cs}|\) and \(|V_{cd}|\) are known to \(\pm 5\%\) and \(\pm 15\%\) respectively \(\[3, 13\]\). From the branching ratios for the semileptonic decays \(D^0 \rightarrow \pi^-l^+\nu_l\) and \(D^0 \rightarrow K^-l^+\nu_l\), the ratio \(|V_{cd}|/|V_{cs}|\) should be determined in Charm2000 with a statistical accuracy of \(\sim 10^{-3}\).

### 3.4. Hadronic decays

Hadronic decays of mesons containing heavy quarks have many interesting applications. As noted above, they can be used to search for direct CP asymmetries, the size of which depends on final-state phase shifts. The phase shifts can be studied with branching-ratio and Dalitz-plot analyses \(\[3\]\). Such studies test nonperturbative
QCD models and are relevant to direct CP violation in beauty \cite{71} and charm \cite{12,20} decays. The resonant substructure in charm decay to multi-particle final states can also be a QCD laboratory, with the possibility of clarifying the questions of existence of glueballs and gluonic hybrids \cite{73,74}.

4. A Next-Generation Charm Spectrometer

A proposal is under development for a new Fermilab experiment to reconstruct $\approx 4 \times 10^8$ charm decays, $\approx 2000$ times the largest extant charm sample, in the Year-$\approx 2000$ fixed-target run. The spectrometer (Figs. 2-3) is planned to be compact and of moderate cost (e.g. substantially cheaper than HERA-B \cite{75}), but with large acceptance, good resolution, and high-rate tracking and particle identification. Tracking is done exclusively with silicon or diamond \cite{76} and scintillating-fiber \cite{77} detectors, allowing operation at a 5 MHz interaction rate. A fast ring-imaging Cherenkov counter \cite{78} provides hadron identification, and calorimeters (possibly augmented by a TRD) identify electrons and allow first-level triggering on transverse energy. Triggering efficiently on charm while maintaining high livetime and a manageable data rate to tape ($\lesssim 100$ MB/s) is a significant challenge, requiring hardware decay-vertex triggers \cite{79}; first-level “optical” triggers may play a significant role \cite{80,81}. (More detailed discussions may be found in \cite{82} and \cite{83}).

5. Yield

In 800 GeV proton collisions with a high-$A$ target, charm is produced at a rate of $\approx 7 \times 10^{-3}$ per interaction \cite{84}. Thus at a 5 MHz interaction rate in a typical fixed-target run of $3 \times 10^6$ live beam seconds, $10^{11}$ charmed particles are produced. The reconstructed-event yields in representative modes are estimated in Table 2, with efficiencies derated for all-hadronic modes under the assumption that the optical trigger described in \cite{85} is used for those modes. For leptonic modes, the first-level trigger rate should be sufficiently low to be recorded directly. The second half of the table gives yields extrapolated by a factor of 2000 from E791. The total reconstructed sample is well in excess of $10^8$ events. Given the factor $\approx 2$ mass-resolution improvement compared to E791, one can infer a factor $\approx 50$ improvement in statistical significance for typical decay modes. No other proposed experiment is competitive in reach.5

6. Conclusions

A fixed-target hadroproduction experiment (Charm2000) capable of reconstructing $>10^8$ charm decays is feasible using detector, trigger, and data acquisition technologies which exist or are under development. A typical factor $\approx 50$ in statistical significance of signals may be expected.

\footnote{While HERA-B could be competitive with Charm2000 as a charm experiment, it lacks the capabilities to trigger efficiently on charm and to acquire the needed large data sample, and it probably has significantly poorer vertex resolution as well.}

\footnote{The CHEOPS Letter of Intent to CERN \cite{86} and the proposed Tau/Charm Factory \cite{87} both aim at $\sim 10^7$ reconstructed charm.}
compared to E791, possibly bringing within reach the observation of Standard-Model CP violation in charm decay, and extending searches for new physics by two orders of magnitude in statistical power.

Acknowledgements

I thank A. Fridman for the invitation to participate, as well as for organizing so stimulating a conference in such memorable surroundings.

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Table 1
Sensitivity to high-impact charm physics.

| Topic                              | Limit* | Charm2000 Reach* | SM prediction |
|------------------------------------|--------|------------------|---------------|
| **Direct CP Viol.**                |        |                  |               |
| $D_s^0 \rightarrow K^- \pi^+$      | -0.009 < $A$ < 0.027 | few $\times 10^{-4}$ | ≈ 0 (CFD) |
| $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ |        |                  |               |
| $D^+ \rightarrow K^+ \pi^-$        | -0.11 < $A$ < 0.16 | few $\times 10^{-3}$ | ≈ 0 (DFSD) |
| $D^0 \rightarrow K^- K^+$          |        |                  |               |
| $D^- \rightarrow K^+ K^- \pi^+$    | -0.14 < $A$ < 0.081 | 10^{-3} | (2.8±0.8) $\times 10^{-3}$ | |
| $D^+ \rightarrow K_{s}^{0} K^+$    | -0.33 < $A$ < 0.094 | 10^{-3} | (−1.5±0.4) $\times 10^{-3}$ | |
| $D^+ \rightarrow \phi \pi^+$       | -0.75 < $A$ < 0.21 | 10^{-3} | 3.3 $\times 10^{-3}$ | |
| $D^+ \rightarrow K_S^0 \pi^+$      |        |                  |               |
| **FCNC**                           |        |                  |               |
| $D_s^0 \rightarrow \mu^+ \mu^-$    | 7.6 $\times 10^{-6}$ | 10^{-7} | < 3 $\times 10^{-15}$ | |
| $D^0 \rightarrow \pi^0 \mu^+ \mu^-$ | 1.7 $\times 10^{-6}$ | 10^{-6} |                  | |
| $D^0 \rightarrow \overline{K}^{0} e^+ e^-$ | 17.0 $\times 10^{-4}$ | 10^{-6} | < 2 $\times 10^{-15}$ | |
| $D^0 \rightarrow K^- \mu^+ \mu^-$ | 2.5 $\times 10^{-4}$ | 10^{-6} | < 2 $\times 10^{-15}$ | |
| $D^0 \rightarrow K^+ e^- e^-$      | 6.6 $\times 10^{-4}$ | few $\times 10^{-7}$ | < 10^{-8} | |
| $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ | 1.8 $\times 10^{-5}$ | few $\times 10^{-7}$ | < 10^{-8} | |
| $D^+ \rightarrow K^+ e^- e^-$      | 4.8 $\times 10^{-5}$ | few $\times 10^{-7}$ | < 10^{-15} | |
| $D^+ \rightarrow K^+ \mu^+ \mu^-$ | 8.5 $\times 10^{-5}$ | few $\times 10^{-7}$ | < 10^{-15} | |
| $D \rightarrow X_u + \gamma$       |        |                  | ≈ 10^{-5} | |
| $D^0 \rightarrow \rho^0 \gamma$   | 1.4 $\times 10^{-4}$ | (1 − 5) $\times 10^{-6}$ | (0.1 − 3.4) $\times 10^{-7}$ | |
| $D^0 \rightarrow \phi \gamma$     | 2 $\times 10^{-4}$ |                  |               | |
| **LF or LN Viol.**                 |        |                  |               |
| $D^0 \rightarrow \mu^+ e^-$        | 1.0 $\times 10^{-4}$ | 10^{-1} | 0 | |
| $D^+ \rightarrow \pi^+ \mu^+ e^+$  | 3.3 $\times 10^{-4}$ | few $\times 10^{-7}$ | 0 | |
| $D^0 \rightarrow K^- \mu^+ \mu^+$ | 3.4 $\times 10^{-4}$ | few $\times 10^{-7}$ | 0 | |
| $D^+ \rightarrow \pi^+ \mu^- \mu^+$ | 2.2 $\times 10^{-4}$ | few $\times 10^{-7}$ | 0 | |
| $D^+ \rightarrow K^- \mu^+ \mu^+$ | 3.3 $\times 10^{-4}$ | few $\times 10^{-7}$ | 0 | |
| $D^+ \rightarrow \rho^- \mu^- \mu^+$ | 5.8 $\times 10^{-4}$ | few $\times 10^{-7}$ | 0 | |
| **Mixing**                         |        |                  |               |
| $D_s^0 \rightarrow K^{\pm} \pi^{\pm}$ | $r < 0.0037$ | $\Delta M_D < 1.3 \times 10^{-4}$ eV | $r < 10^{-5}$ | |
| $D_s^0 \rightarrow K^0 \nu$       |        |                  | 10^{-7} eV | |

*at 90% confidence level
Table 2
Estimated yields of reconstructed decays (antiparticles included) in Charm2000.

| mode               | charm frac. | BR (%) | acceptance x efficiency | Charm2000 yield |
|--------------------|-------------|--------|--------------------------|-----------------|
| \( D^0 \to K^- \pi^+ \) | 0.5         | 4.0    | 0.6 x 0.1                | \( 1.3 \times 10^8 \) |
| \( D^+ \to K^+ \mu\nu \) | 0.25        | 2.7    | 0.4 x 0.25               | \( 7 \times 10^7 \) |
| \( \to K\pi\mu\nu \) | 0.1         | \( \approx 0.1 \) | \( \approx 0.4 \times 0.1 \) | \( \approx 4 \times 10^8 \) |

| analysis*          | E791 yield* |
|--------------------|-------------|
| FCNC               | 37000 ± 200 | (7 ± 0.001) \times 10^7 |
| mixing             | 3200        | \( 0.6 \times 10^7 \) |
| DCSD               | 45?         | \( 10^4 \times 10^5 \) |
|                    | 6 \times 10^7 |

*Note that the cuts used (and hence the event yields) vary depending on the analysis goal, thus the E791 yields display apparent inconsistencies at the factor-of-2 level.

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Do not hallucinate.