A Future Charm Facility\textsuperscript{a}

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Abstract

The “BTeV/C0” experiment at Fermilab could reconstruct \(>10^9\) charm decays, four orders of magnitude beyond the largest extant sample. The experiment is likely to run during Tevatron Run II (ca. 2000–2005). In addition to “programmatic” charm physics such as spectroscopy, lifetimes, and QCD tests, it will have significant new-physics reach in the areas of \(CP\) violation, flavor-changing neutral-current and lepton-number-violating decays, and \(D^0D^0\) mixing, and could observe direct \(CP\) violation in Cabibbo-suppressed \(D\) decays if it occurs at the level predicted by the Standard Model.

1 Introduction

Charm sensitivities have increased exponentially over the last two decades. Current experiments aim to reconstruct \(\sim 10^6\) events, and the \(B\) factories and COMPASS facility\textsuperscript{1} could achieve \(10^7\)-event sensitivity. We are designing an experiment for the Tevatron’s C0 area which could reconstruct \(10^9\) charm decays during Tevatron Run II (ca. 2000–2005). While this “BTeV/C0” effort aims at both charm and beauty physics, I focus here on charm.

Sensitivity at the proposed level will substantially advance such “programmatic” charm physics as spectroscopy, lifetimes, and QCD tests. It will also give substantial new-physics reach in the areas of \(CP\) violation, flavor-changing neutral-current and lepton-number-violating decays, and \(D^0\overline{D}^0\) mixing. If direct \(CP\) violation occurs in Cabibbo-suppressed \(D\) decays at the level predicted by the Standard Model, it could be observable in the BTeV/C0 experiment.

2 Importance of Charm \(CP\)-Violation, Mixing, and Rare-Decay Studies

\(CP\) violation is recognized as one of the central problems of particle physics. The mechanism(s) responsible for it have yet to be definitively established. A

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leading candidate, the Kobayashi-Maskawa (KM) model has the attractive feature of explaining the small size of $K^0$ CP asymmetries as a manifestation of the small mixing between the third quark generation and the first two. Thus in the KM model, large CP asymmetries are expected in the beauty sector. Other models attribute the effect to the exchange of massive particles such as W’s with right-handed couplings or extra Higgs scalars. In these models CP asymmetries should be more “democratic” and may be too small to observe in beauty ($\mathcal{O}(10^{-3})$). Many of these models predict large mixing in charm.

We do not know whether CP violation arises exclusively from any one of these mechanisms, whether many contribute, or whether some other mechanism not yet thought of is the answer. Thus a balanced program of investigation in all available quark (and lepton) sectors is desirable. As is well known, CP-violation, mixing, and rare-decay studies in beauty are the goal of several projects in progress around the world. Such studies in charm are important precisely because the small Standard Model predictions can allow new physics to appear in a striking manner.

3 Charm CP Violation

3.1 Standard Model

Direct CP violation in charm decay is expected in the Standard Model (SM) at the $10^{-3}$ level (see Table 1). In the SM it is significant only for singly Cabibbo-suppressed decays (SCSD), for which tree-level graphs can interfere with penguin diagrams, leading to partial-decay-rate asymmetries:

$$A \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \neq 0,$$

where $\Gamma(D \to f)$ is the decay width for a $D$ meson to final state $f$ and $\Gamma(\bar{D} \to \bar{f})$ that for the CP-conjugate process.

These asymmetries reflect interference due to the CKM phase in combination with phase differences from final-state interactions. Experimental evidence suggests substantial final-state effects in charm decay. For example, the mode $D^0 \to K^0 \bar{K}^0$ occurs with a branching ratio

$$\frac{B(D^0 \to K^0 \bar{K}^0)}{B(D^0 \to K^+ K^-)} = 0.24 \pm 0.09,$$

even though no spectator diagram can produce this final state, and the two possible W-exchange diagrams cancel each other (by the GIM mechanism) to good approximation. This mode could be fed by rescattering of $K^+ K^-$ into $K^0 \bar{K}^0$. 

Table 1: Sensitivity to high-impact charm physics.*

| Topic | Limit† | Reach of \(10^6\)-charm exp‡ | SM prediction |
|-------|--------|------------------------------|---------------|
| Direct CP Viol. | | | |
| \(D^0 \to K^- \pi^+\) | -0.009 < \(A\) < 0.027 | few \(\times 10^{-4}\) | \(\approx 0\) (CFD) |
| \(D^0 \to K^- \pi^+ \pi^-\) | \(10^{-3} - 10^{-2}\) | | \(\approx 0\) (DCSD) |
| \(D^0 \to K^+ \pi^-\) | few \(\times 10^{-3}\) | | \(\approx 0\) (DCSD) |
| \(D^+ \to K^- K^+\) | -0.11 < \(A\) < 0.16 | 10^{-3} | \(0.13 \pm 0.8\) \(\times 10^{-3}\) |
| \(D^+ \to K^- K^+ \pi^+\) | -0.028 < \(A\) < 0.166 | 10^{-3} | |
| \(D^+ \to K^- K^+ K^+\) | -0.062 < \(A\) < 0.034 | 10^{-3} | |
| \(D^+ \to K^- K^+ K^+\) | -0.092 < \(A\) < 0.072 | 10^{-3} | \(2.8 \pm 0.8\) \(\times 10^{-3}\) |
| \(D^+ \to \phi \pi^+\) | -0.087 < \(A\) < 0.031 | 10^{-3} | |
| \(D^+ \to \pi^- \pi^+ \pi^+\) | -0.086 < \(A\) < 0.052 | 10^{-3} | \((-2.3 \pm 0.6) \times 10^{-3}\) |
| \(D^+ \to \rho^0 \pi^+\) | few \(\times 10^{-4}\) | | \((-1.5 \pm 0.4) \times 10^{-3}\) |
| \(D^+ \to \eta \pi^+\) | few \(\times 10^{-4}\) | | 3.3 \(\times 10^{-3}\) |
| \(D^+ \to K_S \pi^+\) | few \(\times 10^{-4}\) | | |
| Indirect CP Viol. | | | |
| \(D'' \to \pi^+ \pi^-\) | few \(\times 10^{-4}\) | | \(\approx 0\) |
| FCNC | | | |
| \(D'' \to \mu^+ \mu^-\) | 7.6 \(\times 10^{-6}\) | 10^{-7} | \(< 3 \times 10^{-15}\) |
| \(D^0 \to \pi^0 \mu^+ \mu^-\) | 1.7 \(\times 10^{-4}\) | 10^{-6} | |
| \(D^0 \to K^0 \phi \pi^-\) | 17.0 \(\times 10^{-4}\) | 10^{-6} | \(< 2 \times 10^{-15}\) |
| \(D^0 \to K^0 \mu^+ \mu^-\) | 2.5 \(\times 10^{-4}\) | 10^{-6} | \(< 2 \times 10^{-15}\) |
| \(D^+ \to \pi^+ \pi^+ \pi^-\) | 6.6 \(\times 10^{-5}\) | few \(\times 10^{-7}\) | \(< 10^{-8}\) |
| \(D^+ \to \pi^+ \pi^+ \pi^-\) | 1.8 \(\times 10^{-5}\) | few \(\times 10^{-7}\) | \(< 10^{-8}\) |
| \(D^+ \to K^+ \pi^+ \pi^-\) | 4.8 \(\times 10^{-3}\) | few \(\times 10^{-7}\) | \(< 10^{-15}\) |
| \(D^+ \to K^+ \mu^+ \mu^-\) | 8.5 \(\times 10^{-5}\) | few \(\times 10^{-7}\) | \(< 10^{-15}\) |
| \(D^0 \to X_S + \gamma\) | few \(\times 10^{-7}\) | \(< 10^{-5}\) | \(< 10^{-15}\) |
| \(D^0 \to \rho^0 \gamma\) | few \(\times 10^{-4}\) | \(< 10^{-5}\) | (0.1 – 3.4) \(\times 10^{-5}\) |
| LF or LN Viol. | | | |
| \(D'' \to \mu^+ e^-\) | 1.0 \(\times 10^{-4}\) | 10^{-7} | | |
| \(D^+ \to \pi^+ \mu^+ e^-\) | 3.3 \(\times 10^{-3}\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to K^+ \mu^+ \pi^-\) | 3.4 \(\times 10^{-3}\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to \pi^- \mu^+ \mu^-\) | 2.2 \(\times 10^{-4}\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to K^- \mu^+ \mu^-\) | 3.3 \(\times 10^{-4}\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to \rho^- \mu^+ \mu^-\) | 5.8 \(\times 10^{-4}\) | few \(\times 10^{-7}\) | 0 |
| Mixing | | | |
| \(\overline{D^0} \to K^+ \pi^\pm\) | \(r < 0.0037\) | \(\Delta M_D < 1.3 \times 10^{-4}\) eV | \(r < 10^{-5}\) |
| \(\overline{D^0} \to K^\ell \nu\) | \(\Delta M_D < 10^{-5}\) eV | \(r < 10^{-5}\) | 10^{-7} eV |

* To save space, sources for the measurements and predictions in this table are not cited here; most may be found in Refs. [1] and [2].
† at 90% confidence level.
Large final-state effects are also evident in the case of multibody charm decays, where Dalitz-plot analyses reveal appreciable phase differences. These and similar observations underlie the expectation of $\mathcal{O}(10^{-3})$ direct $CP$ asymmetries in charm.

Additional SM mechanisms for charm $CP$ violation include $K^0$ mixing and possible mixing with glueballs or gluonic hybrids. As emphasized by Xing, $K^0$ mixing leads to $CP$ asymmetries of $\approx 2 \text{Re}(\epsilon_K) = 3.3 \times 10^{-3}$ in such decays as $D^+ \rightarrow K_S \pi^+$ and $D^+ \rightarrow K_S \ell \nu$. While perhaps not as interesting as direct charm $CP$ violation, this effect might provide a calibration for systematic effects in the measurement of small asymmetries. As discussed below, it could also represent a unique window into new physics. Close and Lipkin make the intriguing suggestion that $D$'s could be mixed with gluonic-hybrid states, with consequent large $CP$-violating effects.

At present the best limits on direct $CP$ violation in Cabibbo-suppressed charm decay come from Fermilab E687 and E791 and CLEO (Table 1). In fixed-target experiments, to correct for the production asymmetry of $D$ vs. $\bar{D}$, the asymmetry in a Cabibbo-suppressed mode is normalized to that observed in the corresponding Cabibbo-favored (CFD) mode; this also has the effect of reducing sensitivity to such systematic effects as trigger, reconstruction, and particle-identification efficiency differences for particles vs. antiparticles. In E687 $\approx 10\%$ sensitivity is achieved. By extrapolation from E687, the definitive establishment of a $10^{-3}$ asymmetry requires $\approx 10^9$ reconstructed $D$'s, to give $\approx 10^7$ reconstructed charged and (tagged) neutral $D$'s in SCSD modes.

Although the ratiometric nature of these measurements makes them intrinsically insensitive to systematic effects, at the sub-$10^{-3}$ level careful attention will be required to keep systematic uncertainties from dominating.

### 3.2 Beyond the Standard Model

For several reasons, the charm sector is an excellent place to look for $CP$ violation arising from physics beyond the Standard Model:

- The top-quark loops that in the Standard Model dominate $CP$ violation in the strange and beauty sectors are absent, creating a low-background window for new physics.

- New physics may couple differently to up-type and down-type quarks or couple to quark mass.

- Compared to beauty, the large production cross sections allow much larger event samples to be acquired, and the branching ratios to final states of interest are also larger.
Many extensions of the Standard Model predict observable effects in charm. Direct $CP$ violation in Cabibbo-favored or doubly Cabibbo-suppressed (DCSD) modes would be a clear signature for new physics. Asymmetries in these as well as in SCSD modes could reach $\sim 10^{-2}$ in such scenarios as non-minimal supersymmetry and in left-right-symmetric models. Bigi has pointed out that a small new-physics contribution to the DCSD rate could amplify the SM $K^0$-induced asymmetries to $O(10^{-2})$ as well.

Many authors have recently emphasized the possibility of observable indirect $CP$ violation in charm. This of course depends on charm mixing, which has not been established experimentally. However, the observation of a wrong-sign signal (which may be mixing, DCSD, or some mixture of the two) at CLEO has stimulated theorists to consider the large variety of extensions to the SM in which $D^0$ and $\bar{D}^0$ can display appreciable $CP$-violating mixing. These include flavor-changing Higgs exchange, a fourth generation, $Z$-mediated FCNC’s, left-right symmetry, supersymmetry with quark-squark alignment, leptoquarks, etc. At the level discussed in the literature, such effects are likely to be observable in a $10^8$-to-$10^9$-charm experiment.

As a specific example, I consider a possible indirect $CP$ asymmetry in $D^0(\bar{D}^0) \to \pi^+\pi^-$. We would expect $\sim 10^7$ tagged $\pi^+\pi^-$ decays per few $\times 10^9$ reconstructed charm, giving $< 10^{-3}$ sensitivity. Since here the final state is a $CP$ eigenstate, the $CP$ asymmetry is independent of final-state phases and thus directly measures the new-physics phase.

4 Other charm physics

The BTeV/C0 experiment will have unprecedented reach in all areas of charm physics, including tests of QCD and HQET in meson and baryon spectroscopy and lifetimes, charm production, Dalitz-plot analyses, semileptonic form factors, extraction of CKM elements, etc. Space restrictions preclude further discussion here.

5 Experimental Apparatus

Fig. 1 is a sketch of the BTeV/C0 spectrometer as currently conceived. The spectrometer is designed for the Tevatron C0 collider interaction hall, to be upgraded and expanded during the 1998 Main Injector construction period. It differs from existing collider experiments in that it focuses on heavy-quark states produced in the “forward” direction ($|\tan \theta| \leq 0.3$). This approach allows
optimal decay-time resolution and is also advantageous for hadron identification.

The apparatus must have high interaction-rate capability, large acceptance, an efficient charm trigger, high-speed and high-capacity data acquisition, good mass and vertex resolution, and good particle identification. Of these requirements, the most challenging are the trigger and the particle identification. We intend to trigger primarily on the presence of a decay vertex separated from the primary vertex. To reduce occupancy and facilitate vertex reconstruction at trigger level 1, pixel detectors will be used for vertex reconstruction. For efficient, reliable, and compact particle identification, we will build a ring-imaging Cherenkov counter. In other respects the spectrometer will resemble existing large-aperture fixed-target heavy-quark experiments.

6 Sensitivity Estimate

Our charm sensitivity goal might be achieved in either collider or fixed-target mode. During Tevatron Run II, much early running at C0 may be in fixed-target mode, e.g. using a wire target in the beam halo. We have estimated the fixed-target reconstructed-event yield at \( \approx 1 \times 10^8 \) per \( 10^7 \) seconds of running for an experiment operating at a 1-MHz interaction rate. Given the higher production cross section, comparable or greater sensitivity could be available in collider mode even with reduced running time. In addition, we anticipate increasing the interaction rate beyond 1 MHz as the Tevatron bunch separation is reduced from 396 to 132 ns. Ultimately \( \approx 5 \) MHz could be feasible, leading to \( > 10^9 \) charm decays reconstructed.

Whether fixed-target or collider mode is better for charm physics is a detailed question which probably cannot be answered definitively until data are taken. For one thing, the forward charm-production cross section has not yet been measured in 2 TeV \( pp \) collisions. There are also subtleties, for example...
biases in mixing studies may arise from \( b \to c \) cascade decays. These would be suppressed by two orders of magnitude in fixed-target relative to collider mode, due to the reduced beauty production cross section.

7 Conclusions

A hadroproduction experiment capable of reconstructing \( > 10^9 \) charm events is feasible using detector, trigger, and data acquisition technologies that exist or are under development. Such an experiment could observe direct \( CP \) violation in charm decay at the level expected in the Standard Model and substantially extend the discovery reach for new physics.

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