Experimental prospects for CP violation in charm

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Abstract

Experimental sensitivity to CP violation in charm decay is beginning to approach the interesting regime ($\sim 10^{-3}$) in which new physics may be manifest. In the early years of the 21st century, if the technical challenges can be met, the proposed BTeV experiment should have the best sensitivity for rare effects both in charm and in beauty.

1 Charm CP Violation in the Standard Model and Beyond

The Standard Model (SM) predicts direct CP violation at the $\mathcal{O}(10^{-3})$ level in singly Cabibbo-suppressed (SCS) charm decays due to the interference of tree-level processes with penguins (Fig. 1). The observation of CP asymmetries substantially larger than this could be unambiguous evidence of new physics, as would almost any observation of CP violation in Cabibbo-favored (CF) or doubly Cabibbo-suppressed (DCS) charm decays.

A variety of extensions of the Standard Model have been considered in which charm CP asymmetries could be as large as $\mathcal{O}(10^{-2})$. These include models with leptoquarks, extra Higgs doublets (e.g. non-minimal supersymmetry), a fourth generation, or right-handed weak currents. In addition, two Standard Model possibilities for large CP asymmetries in charm have been

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$^b$In $D^0$ (but not charged-$D$) decays, $\mathcal{O}(10^{-3})$ CP asymmetries may be possible in the SM due to interference between DCS and mixing amplitudes.
Figure 1: Example of Cabibbo-suppressed $D^+$ decay that can proceed via both (a) tree and (b) penguin diagrams.

Table 1: World-average charm CP asymmetries (from Ref. 3).

| Particle Mode | Asymmetry       |
|---------------|-----------------|
| $D^\pm$       | $K^\mp K^- \pi^\pm$ $-0.017 \pm 0.027$ |
|               | $K^\pm K^{*0}$ $-0.02 \pm 0.05$ |
|               | $\phi \pi^\pm$ $-0.014 \pm 0.033$ |
|               | $\pi^+ \pi^- \pi^\pm$ $-0.02 \pm 0.04$ |
| $D^0$         | $K^+ K^-$ $0.026 \pm 0.035$ |
|               | $\pi^+ \pi^- $ $-0.05 \pm 0.08$ |
|               | $K_S \phi$ $-0.03 \pm 0.09$ |
|               | $K_S \pi^0$ $-0.018 \pm 0.030$ |

discussed: asymmetries due to $K^0$ mixing in e.g. $D^\pm \rightarrow K_S \pi^\pm$, and the possibility that $D$ mesons mix with glueballs or gluonic hybrids. 9

2 Limits on Charm CP Violation

Exponentially-increasing charm event samples have led to substantially improved CP-violation limits over time. The most sensitive limits come from Fermilab fixed-target experiments E791 10 and E687 11 and from CLEO II. 12 These have been combined into world averages by the Particle Data Group for the 1998 Review of Particle Physics (Table 1). 13 No significant signals have been observed, and most limits are in the range of several percent. There is thus a substantial discovery window for new physics in SCS modes, and an even larger one for CF and DCS modes (for which almost no limits are available). 14

These time-integrated $CP$ asymmetries are defined as

$$A_{CP} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}.$$  (1)
Note that while not explicitly time-dependent, $A_{CP}$ is sensitive to decay time through the vertex-separation cuts used to suppress non-charm background. For $D^0$ decays, it is thus sensitive to both direct and indirect $CP$ violation.

When (as in fixed-target experiments) the initial state is non-$CP$-symmetric, the observed rate asymmetry in a given mode must be corrected for $D^-D^+$ production asymmetry. E687 and E791 therefore normalize their observed rates in SCS modes to those in CF modes, for example,

$$A_{CP}(D^0) = \frac{\frac{N(D^0 \to f)}{N(D^0 \to K^- \pi^+)} - \frac{N(D^0 \to f)}{N(D^0 \to K^+ \pi^-)}}{\frac{N(D^0 \to f)}{N(D^0 \to K^- \pi^+)} + \frac{N(D^0 \to f)}{N(D^0 \to K^+ \pi^-)}}.$$  

Equation (2)

Acceptances and efficiencies tend to cancel in Eq. 2, reducing systematic uncertainties.

3 Prospects for Improved Sensitivity

Several experiments soon to take data are expected to surpass current sensitivities. Current and future experiments are summarized in Table 2. Since $CP$-violation sensitivity depends in complicated ways on reconstruction and particle-ID efficiency for various modes, optimization of vertex cuts, $D^*$-tagging efficiency (for $D^0$ modes), etc., we use here simple overall benchmarks rather than detailed estimates. These are total number of charm decays produced or reconstructed and total number of $D^0 \to K^\mp \pi^\pm$ decays produced or reconstructed. We scale from current experiments according to the square root of one of these benchmark numbers to obtain an estimated $CP$ reach in each case, recognizing that this procedure is at best approximate and addresses only the statistical component of $CP$ sensitivity.

The $B$ Factories and CLEO III are expected to have the best charm $CP$ reach among approved future experiments. (While HERA-B has the highest charm production rate, it is likely to have poor trigger efficiency for charm due to $p_t$ requirements imposed at the trigger level.) In multi-year runs, the combined reach of these experiments could be approximately an order of magnitude better than current limits, reaching the few $\times 10^{-3}$ level.

We have seen above that this sensitivity is unlikely to be sufficient to observe Standard Model $CP$ violation in charm, though it may suffice for the discovery of non-SM effects if they are large. As we will see, the proposed BTeV experiment at the Tevatron should be able to achieve $\sim 10^{-4}$ sensitivity, bringing even SM effects within reach.
Table 2: Current and approved future experiments with charm CP-violation sensitivity.

| Exp’t            | All charm decays prod. | $\bar{B}^0 \rightarrow K^{\mp}\pi^{\pm}$ prod. | $\sigma(A_{CP})$ | (SCS) |
|------------------|------------------------|-----------------------------------------------|-----------------|-------|
| FNAL E687        | 0.8 x 10^7             | 1.2 x 10^6                                   | ≈ 0.1           |       |
| FNAL E791        | 10^8                   | 2.5 x 10^5                                   | ≈ 0.05          |       |
| CLEO II*         | 2.7 x 10^6             | 1.0 x 10^5                                   | ≈ 0.05          |       |
| FOCUS (FNAL E831)| 10^6                   | 1.8 x 10^4                                   | ≈ 0.03          |       |
| COMPASS          |                        | 7 x 10^4                                     | ≈ 0.03          |       |
| HERA-B           | few x 10^10 /yr         |                                              | ?               |       |
| B Factories, CLEO III | 3 x 10^7 /yr     |                                              | ≈ 0.01          |       |

*CLEO II sensitivity given as of Ref. 12; additional data are being accumulated, and the final CLEO II sample should be substantially larger.

4 The BTeV Experiment

BTeV is an approved R&D program at Fermilab aimed at proposing a collider charm and beauty experiment for Tevatron Run II and beyond. Its main physics goals are to search for CP violation, mixing, and rare flavor-changing neutral-current decays of beauty and charm at unprecedented levels of sensitivity. Each year of BTeV collider operation is expected to produce $O(10^{11})$ $b$ hadrons and $O(10^{12})$ $c$ hadrons, to be compared with $O(10^7)$ of each available at the $B$ Factories and $O(10^9)$ and $O(10^{10})$ per year at HERA-B. The BTeV spectrometer is being designed to make optimal use of the produced samples, avoiding many of the compromises necessary in general-purpose detectors.

Since $B$ physics is a major goal of BTeV, we here summarize projected sensitivities for beauty as well as charm physics. More detailed discussions, both of the proposed apparatus and of its physics reach, may be found in Refs. 16, 17.

4.1 The BTeV Spectrometer

The proposed BTeV spectrometer (Fig. 2) covers the forward and backward regions at the new C0 Tevatron interaction area. The instrumented angular range is $0.01 \lesssim |\tan \theta| \lesssim 0.3$, corresponding to the approximate pseudorapidity range $1.5 \lesssim \eta \lesssim 6$ for the parent particle. Monte Carlo simulation shows that such coverage gives $\approx 10$–50% acceptance (depending on mode) for $B$ and $D$ decays. Compared to the “central-geometry” case (e.g. CDF and D0), this “forward-geometry” configuration accepts relatively high-momentum particles (see Fig. 3), allowing better reconstruction of decay proper time. Another advantage is the feasibility of effective charged-hadron identification.
Figure 2: Elevation and plan of the BTeV spectrometer.

Figure 3: Relativistic boost factor $\beta \gamma$ vs. pseudorapidity $\eta$ of $B$ hadrons produced at the Tevatron Collider.
Because QCD mechanisms of $b\bar{b}$ production yield quark pairs that are closely correlated in pseudorapidity ($|\eta_b - \eta_{\bar{b}}| \lesssim 1$), there is little disadvantage in omitting the small-$\eta$ region: when the decay products of one $B$ hadron are detected in the forward (or backward) region, decay products of the second ("tagging") $B$ have a high probability to be detected there also. (And of course, for "same-side" tagging the direction of the other $B$ is immaterial.)

In addition to large acceptance, the apparatus must have high interaction-rate capability, superb vertex reconstruction, an efficient trigger, high-speed and high-capacity data acquisition, good mass resolution, and good particle identification. Of these requirements, the most challenging are the vertexing, the trigger, and the particle identification. It is these challenges that the BTeV R&D program is addressing.

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 (Fig. 4) will be used for vertex reconstruction. For efficient, reliable, and compact particle identification, we will use ring-imaging Cherenkov counters. In other respects the spectrometer layout will resemble that of existing large-aperture fixed-target heavy-quark experiments.

A crucial detail of spectrometer design deserves comment, since it has a large impact on sensitivity. As the size of the gap between the upper and lower halves of the vertex detectors is reduced, for pixel resolution fine enough that multiple scattering dominates, vertex resolution improves linearly. However, there is a minimum gap size below which radiation damage to the pixel detectors becomes unacceptably large. Given these competing requirements, we find that resolution is optimized by use of a square beam hole rather than the horizontal gap shown in Fig. 4.

As an example we consider sensitivity to $B_s$ mixing. Improved vertex resolution helps two ways: both in resolving the extremely rapid $B_s$-$\bar{B}_s$ oscillations, and by enlarging the event sample that passes the vertex cuts needed to suppress background. This is illustrated in Fig. 5, in which the reach in the $B_s$ mixing parameter $x_s$ in the $J/\psi K^*$ and $D_s \pi$ decay modes is compared for the "EoI" vertex-detector configuration (with 12-mm horizontal gap) and for a vertex detector with a 12-mm-square beam hole. The $x_s$ reach is substantially better with the square hole. For example, if $x_s$ is 60, its determination at $5\sigma$ significance would require two months of running with the square hole but three years with the horizontal gap. The square-hole configuration has now been adopted as the BTeV baseline design.
4.2 BTeV Beauty Sensitivity

Especially for nonleptonic final states, BTeV’s beauty sensitivity is expected to surpass that of all other proposed experiments. Since beauty experiments have many goals, comparing their sensitivities is an involved procedure. Table 3 gives a representative set of benchmarks.

4.3 BTeV Charm Sensitivity

BTeV’s charm sensitivity depends on running mode. BTeV can operate both in collider and fixed-target modes. The latter mode is achieved by suspending a thin wire or small pellet in the halo of the proton or antiproton beam. Given the accelerator upgrades needed to achieve high-luminosity $p\bar{p}$ collisions at C0, fixed-target running may occur before collider running. The huge increase in $b\bar{b}$ cross section from $\sqrt{s} = 0.043$ to 2 TeV$^2$ means that significant beauty sensitivity is available only in collider mode. However, useful charm sensitivity may be available in fixed-target mode.

Table 4 compares charm sensitivity in the two running modes. There is some uncertainty in each case. For example, the optimal choice of material for
Figure 5: BTeV reach in $x_s$ for two $B_s$ decay modes, comparing square-hole configuration with horizontal-gap configuration.

Table 3: Representative examples of BTeV $b$-physics reach (from Ref. 17).

| Measurement                              | Accuracy/10^7 s |
|------------------------------------------|-----------------|
| $x_s$                                    | $> 80$          |
| $\sin 2\beta$ (using $B^0 \to \psi K_S$) | $\pm 0.013$    |
| $A_{CP}(B^0 \to \pi^+ \pi^-)$           | $\pm 0.013^*$   |
| $\gamma$ (using $D_s K^-$)               | $\pm \approx 8^0$ |
| $\gamma$ (using $D^0 K^-$)               | $\pm \approx 8^0$ |
| $BR(B^- \to K^- \mu^+ \mu^-)$           | $5 \times 10^{-8}$ (at $4\sigma$)* |

*These results are for a vertex detector with a horizontal beam gap, as opposed to the square beam hole used in the other simulations.
Table 4: Charm sensitivity in BTeV fixed-target and collider modes.

| Quantity                  | FT               | Collider         |
|---------------------------|------------------|------------------|
| Running time              | $10^{7}$ s       | $10^{7}$ s       |
| Interaction rate          | $2 \times 10^{6}$ s$^{-1}$ | $1.5 \times 10^{7}$ s$^{-1}$ |
| $\overline{D}^0$/interaction | $6.5 \times 10^{-4} A^{0.29*}$ | 1%?†              |
| $A^{0.29}$                | 2 - 4.5 (C - W)  | 1                |
| $BR(D^0 \rightarrow K^-\pi^+)$ | 3.85%          | 3.85%            |
| $\overline{D}^0 \rightarrow K\pi$ produced | $(1 - 2.3) \times 10^9$ | $6 \times 10^{10}$? |
| Acceptance                | 35%              | 27%              |
| Trigger eff.              | 15%              | 11%              |
| Reconst. eff.             | 40%              | 40%              |
| $D^0 \rightarrow K\pi$ reconstr. | $(2 - 5) \times 10^7$ | $7 \times 10^8$? |

*Extrapolated from measurements at $\sqrt{s} = 39$ GeV.
†Assumed since no measurement is yet available.

the fixed target is not yet clear, so we consider a range from carbon to tungsten. For collider, the charm production cross section has not yet been measured, so we use an educated guess. Also, in both cases efficiency estimates can be expected to evolve as our simulations become more sophisticated. However, the potential is clear. Scaling from FNAL E791, we may expect $CP$ sensitivity in SCS modes at the level of a few $\times 10^{-4}$ per year of collider running. If systematic uncertainties can be controlled, BTeV should be able to observe significant $CP$ asymmetries in charm decay even at the Standard Model level.

5 Conclusions

It is becoming increasingly clear that full understanding of the mechanisms of $B$ decay and their bearing on the unitarity triangle will require the large beauty event samples available only in hadroproduction. Given the complexity of these analyses it may be that unexpected effects in charm decay will provide the first evidence of physics beyond the Standard Model. By providing large well-measured samples both of beauty and of charm, BTeV could be the key experiment that will lead to a breakthrough in our understanding in the early years of the next century.
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