

Prospects for Charm CP Violation Studies in BTeV*

Daniel M. Kaplan[†]

Illinois Institute of Technology, Chicago, IL 60616

for the BTeV Collaboration

Abstract

The BTeV experiment at Fermilab could reconstruct $>10^9$ charm decays, three orders of magnitude beyond the largest extant sample. The experiment is likely to run during Tevatron Run II. It will have significant new-physics reach in the areas of charm CP violation, flavor-changing neutral-current and lepton-number-violating decays, and $D^0\overline{D}^0$ mixing, and could observe direct CP violation in Cabibbo-suppressed D decays if it occurs at the level predicted by the Standard Model.

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[†]kaplan@fnal.gov

I. INTRODUCTION

Particle physics at the turn of the millennium faces 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 be studied only 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 [1–3]. Because in the charm sector the Standard Model (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 [4, 5], which for new-physics searches constitute backgrounds.

II. CHARM CP VIOLATION

Both direct and indirect CP violation are possible in charm decay. The Standard Model (SM) predicts direct CP violation in singly Cabibbo-suppressed (SCS) charm decays at the $\mathcal{O}(10^{-3})$ level [6], arising from the interference of tree-level processes with penguins (Fig. 1). The observation of CP asymmetries substantially larger than this would be unambiguous evidence for new physics, as would almost any observation of direct CP violation in Cabibbo-favored (CF) or doubly Cabibbo-suppressed (DCS) charm decays. The experimental signature for direct CP violation is a difference in partial decay rates between particle and antiparticle:

$$A \equiv \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})} \neq 0, \quad (1)$$

where f and \bar{f} are CP -conjugate final states or (for CP eigenstates) $f = \bar{f}$. In the latter case the two processes of Eq. 1 are distinguished by initial-state tagging ($D^{*\pm} \rightarrow (\bar{D})^0 \pi^\pm$), while in the former case the final states are “self-tagging.” Rates observed in the self-tagging modes typically need to be corrected for production-rate or detection-efficiency asymmetries between particle and antiparticle, hence what is reported is usually an asymmetry normalized to that in a CF mode.

Indirect charm CP violation can arise through the interference of DCS and mixing amplitudes, *e.g.* (for “wrong-sign” decay of the D^0),

$$\Gamma(D^0 \rightarrow K^+ \pi^-) = |B|^2 \left| \frac{q}{p} \right|^2 \frac{e^{-\Gamma t}}{4} \left\{ 4|\lambda|^2 + \left(\Delta M^2 + \frac{\Delta \Gamma^2}{4} \right) t^2 + [2\text{Re}(\lambda)\Delta\Gamma + 4\text{Im}(\lambda)\Delta M]t \right\} \quad (2)$$

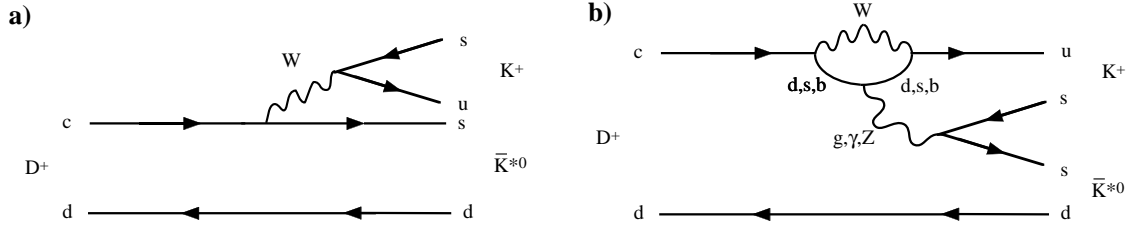


FIG. 1: Example of Cabibbo-suppressed D^+ decay that can proceed via both (a) tree and (b) penguin diagrams.

(Here we use the notation of Refs. [7] and [8].) In Eq. 2 the first term on the right-hand side is the DCS contribution, which peaks at $t = 0$; the second is the mixing contribution, which peaks at two D^0 lifetimes due to the factor t^2 ; and the third term reflects interference between mixing and DCS decay and peaks at one lifetime due to the factor t . Given the small values of ΔM and $\Delta\Gamma$ for the D^0 [9], the interference term (which is linear in ΔM and $\Delta\Gamma$) may be more easily detectable than the pure mixing term. CP is violated if $\lambda \neq \bar{\lambda}$, where λ ($\bar{\lambda}$) is the DCS amplitude for D^0 (\bar{D}^0).

A variety of extensions of the Standard Model have been considered [10] in which charm CP asymmetries could be as large as $\mathcal{O}(10^{-2})$. These include models with leptoquarks [11], extra Higgs doublets (*e.g.* non-minimal supersymmetry [12]), a fourth generation [2, 13], or right-handed weak currents [2, 14]. In addition, two Standard Model possibilities for large CP asymmetries in charm have been discussed: asymmetries due to K^0 mixing in *e.g.* $D^\pm \rightarrow K_S \pi^\pm$ [15], and the intriguing possibility that D mesons mix with glueballs or gluonic hybrids [16].

Recent experimental hints [17–19] that D^0 mixing may be on the verge of detection have led to renewed interest in this physics [20, 21]. The experimental situation is that both CLEO and FOCUS have observed effects at the $\approx 2\sigma$ level: CLEO measures $y' = (-2.5^{+1.4}_{-1.6} \pm 0.3)\%$ (for their most general fit) [17], where $y' \equiv y \cos \delta - x \sin \delta$, $x \equiv \Delta M/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$, and δ is the strong phase between the DCS and CF amplitudes; and FOCUS obtains [18] $y = (3.42 \pm 1.39 \pm 0.74)\%$. (These results, while superficially contradictory, can be reconciled for a range of possible choices of δ ; whether such large δ is theoretically plausible is a subject of current debate [21].)

III. EXPERIMENTAL PROSPECTS

Current sensitivities to charm CP violation are summarized in Table I. These are based on samples of up to $\sim 10^6$ reconstructed charm decays obtained in the CLEO and FOCUS

TABLE I: World-average charm CP asymmetries (from Ref. [9]).

Particle	Mode	Asymmetry
D^\pm	$K^+K^-\pi^\pm$	-0.017 ± 0.027
	$K^\pm K^{*0}$	-0.02 ± 0.05
	$\phi\pi^\pm$	-0.014 ± 0.033
	$\pi^+\pi^-\pi^\pm$	-0.02 ± 0.04
$(\overline{D})^0$	K^+K^-	0.026 ± 0.035
	$\pi^+\pi^-$	-0.05 ± 0.08
	$K_S\phi$	-0.03 ± 0.09
	$K_S\pi^0$	-0.018 ± 0.030
	$K^\pm\pi^\mp$	0.02 ± 0.20

experiments. The B factories can be expected to obtain samples an order of magnitude larger than these, which should push CP -violation limits down to the one-to-few-% level, and the COMPASS experiment at CERN may also be competitive at this level [22].

Other experiments that could potentially extend charm CP -violation sensitivity include HERA- B , LHC b , and BTeV. HERA- B has operated so far in a mode in which charm decays are efficiently rejected by the trigger, and a significant upgrade of their DAQ bandwidth would be required in order to record a substantial sample of hadronic charm decays. Similarly, LHC b is designed to reject charm at trigger level in order to concentrate on beauty.

BTeV is an approved Fermilab experiment that will use the Tevatron Collider to study heavy-quark physics. BTeV data-taking is planned to commence in Tevatron Run IIB (starting about 2006). To achieve the highest possible sensitivity to mixing, CP violation, and rare decays in charm as well as beauty, a very ambitious trigger system is envisioned that will examine *every* beam crossing for evidence of secondary vertices [23]. To do this it will make use of information from a unique, high-speed, silicon-pixel vertex detector [24, 25] located inside the dipole spectrometer magnet (see Fig. 2). The design goal for this trigger is an efficiency better than 50% for B events of interest.

Triggering on decay vertices is more difficult for charm than for beauty, since charm lifetimes are shorter and the typical transverse momenta of charm decay products (important for vertex resolution) are lower. Fig. 3 shows the results of a Geant simulation of the BTeV apparatus,

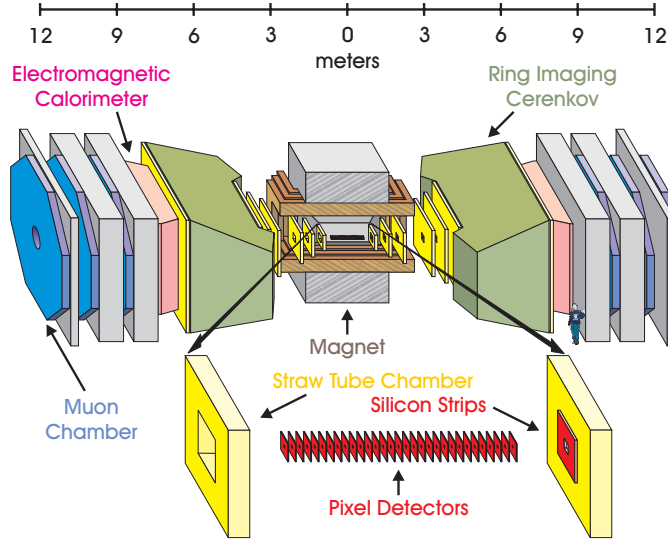


FIG. 2: Layout of BTeV spectrometer; note that the pixel vertex detector is located within the dipole spectrometer magnet centered on the interaction region.

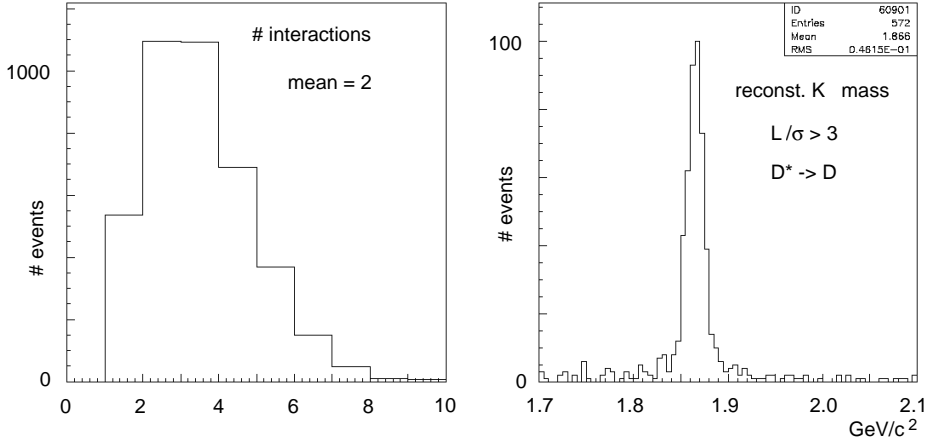


FIG. 3: Preliminary results from a Geant simulation of 4000 D^* decays in BTeV [27].

indicating about 1% efficiency for the decay chain $D^{*+} \rightarrow D^0 \rightarrow K^- \pi^+$, including geometric acceptance, trigger efficiency, and offline reconstruction efficiency. (The vertex trigger efficiency is here assumed to be about 10%, based on previous simulation results [26], but this needs to be rechecked in light of the recent evolution of our vertex trigger algorithm [23].)

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 the total

number of charm decays produced or reconstructed and the total number of $(\overline{D}^0 \rightarrow K^\mp \pi^\pm)$ 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, recognizing that this procedure is at best approximate and addresses only the statistical component of CP sensitivity. These estimates suggest that BTeV is likely to reconstruct about 10^8 such events per year, or $> 10^9$ -event overall charm sensitivity summing over all modes.

Future simulation work should allow more detailed BTeV charm sensitivity estimates, including both statistical and systematic effects. However, at the present level of understanding, sensitivity below the 10^{-3} level looks possible in BTeV, thus even charm CP asymmetries at the Standard Model level may be detectable.

BTeV running might be staged, with wire-target running (à la HERA-B) in the years before a high-luminosity $\bar{p}p$ interaction region can be provided for us. Although collider running is required for competitive beauty sensitivity, charm sensitivity may be comparable in fixed-target and collider modes.

IV. CONCLUSIONS

Unique among near-term heavy-quark hadroproduction experiments, BTeV will have substantial and broad sensitivity to charm events and should be the leading charm experiment in the latter half of this decade. Sensitivity to charm CP violation even at the Standard Model level is possible. Observation of a larger effect could be important evidence for new physics beyond the Standard Model.

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- [1] J. L. Hewett, “Searching for New Physics with Charm,” *Proc. LISHEP95 Workshop*, Rio de Janeiro, Brazil, Feb. 20–22, 1995, p. 171.
 - [2] S. Pakvasa, “Charm as Probe of New Physics,” in **The Future of High-Sensitivity Charm Experiments**, D. M. Kaplan and S. Kwan, eds., FERMILAB-Conf-94/190 (1994), p. 85.
 - [3] M. D. Sokoloff and D. M. Kaplan, “Physics of an Ultrahigh-Statistics Charm Experiment,” in **Heavy Quarks at Fixed Target**, B. Cox, ed., Frascati Physics Series no. 3 (1994), p. 411.
 - [4] For a recent review see J. L. Rosner, “CP Violation: Past, Present, and Future,” hep-ph/0101033, Braz. J. Phys. **31** (2001) 147.

- [5] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. **87**, 091801 (2001); K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001).
- [6] M. Golden and B. Grinstein, *Phys. Lett. B* **222**, 501 (1989); F. Buccella *et al.*, *Phys. Lett. B* **302**, 319 (1993) and *Phys. Rev. D* **51**, 3478 (1995); A. Pugliese and P. Santorelli, “Two Body Decays of D Mesons and CP Violating Asymmetries in Charged D Meson Decays,” *Proc. Third Workshop on the Tau/Charm Factory*, Marbella, Spain, 1–6 June 1993, Edition Frontieres (1994), p. 387; G. Burdman, “Charm Mixing and CP Violation in the Standard Model,” in **The Future of High-Sensitivity Charm Experiments**, D. M. Kaplan and S. Kwan, eds., FERMILAB-Conf-94/190 (1994), p. 75.
- [7] G. Blaylock, A. Seiden, and Y. Nir, Phys. Lett. **B355**(1995) 555.
- [8] T. E. Browder and S. Pakvasa, Phys. Lett. **B383** (1996) 475.
- [9] D. E. Groom *et al.* (Particle Data Group), Eur. Phys. J. **C15** (2000) and 2001 update at <http://pdg.lbl.gov>.
- [10] Y. Nir, *Nuovo Cim.* **109A** (1996) 991.
- [11] W. Buchmuller and D. Wyler, Phys. Lett. **177B**, 377 (1986) and Nucl. Phys. **B268**, 621 (1986); M. Leurer, Phys. Rev. Lett. **71**, 1324 (1993).
- [12] I. I. Bigi, in *Heavy Quarks at Fixed Target*, ed. B. Cox, Frascati Physics Series, Vol. 3 (1994), p. 235.
- [13] K. S. Babu *et al.*, *Phys. Lett. B* **205**, 540 (1988); T. G. Rizzo, *Int. J. Mod. Phys. A* **4**, 5401 (1989).
- [14] A. Le Yaouanc, L. Oliver, and J.-C. Raynal, *Phys. Lett. B* **292** (1992) 353.
- [15] Z. Xing, *Phys. Lett. B* **353**, 313 (1995).
- [16] F. E. Close and H. J. Lipkin, *Phys. Lett. B* **372** (1996) 306.
- [17] R. Godang *et al.* (CLEO Collaboration), Phys. Rev. Lett. **84**, 5038 (2000).
- [18] J. M. Link *et al.* (FOCUS Collaboration), Phys. Lett. **B485** (2000) 62.
- [19] D. Cronin-Hennessy *et al.* (CLEO Collaboration), “Mixing and CP Violation in the Decay of Neutral D Mesons at CLEO,” Fourth International Conference on B Physics and CP Violation (BCP4), Ise-Shima, Japan, hep-ex/012006 (2001).
- [20] M. Gronau, Y. Grossman, J. L. Rosner, hep-ph/0103110 (2001); D. Pedrini, J. Phys. G: Nucl. Part. Phys. **27** (2001) 1259; I. I. Y. Bigi and N. Uraltsev, Nucl. Phys. **B592** (2001) 92.
- [21] A. F. Falk, Y. Nir, A. A. Petrov, JHEP **9912** (1999) 19.
- [22] G. Baum *et al.*, CERN-SPSLC-96-14, Mar. 1996.

- [23] D. M. Kaplan, “The BTeV Vertex Trigger System,” these Proceedings.
- [24] A. Kulyavtsev *et al.*, “Proposal for an Experiment to Measure Mixing, CP Violation and Rare Decays in Charm and Beauty Particle Decays at the Fermilab Collider – BTeV,” May 2000.
- [25] D. C. Christian *et al.*, Nucl. Instrum. Meth. **A473** (2001), 152; S. Zimmermann *et al.*, Nucl. Instrum. Meth. **A465** (2000) 224.
- [26] D. M. Kaplan and V. Papavassiliou, in **CP Violation**, X.-H. Guo, M. Sevier, and A. W. Thomas, eds., World Scientific (2000), p. 116.
- [27] Based on simulations carried out by J. Butler and H. Cheung.