

A Future High Statistics Charm Mixing Experiment Using the Fermilab Tevatron

A. J. Schwartz^a

^aPhysics Department, University of Cincinnati, Cincinnati, Ohio 45221

We present an idea for a future D^0 - \bar{D}^0 mixing and CP violation experiment to run at the Fermilab Tevatron. We estimate that in three years of running, such an experiment could reconstruct an order of magnitude more flavor-tagged $D^0 \rightarrow K^+\pi^-$ decays than will be reconstructed by the B -factory experiments with their full data sets. The resulting sensitivity to CP -violating parameters $|q/p|$ and $\text{Arg}(q/p)$ is calculated from a global fit to CP -violating observables, and it is found to be much greater than current world sensitivity.

1. INTRODUCTION

We present an idea to use the Fermilab Tevatron to produce very large samples of D^* mesons that decay via $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+\pi^-$ [1]. The decay time distribution of the “wrong-sign” $D^0 \rightarrow K^+\pi^-$ decay is sensitive to D^0 - \bar{D}^0 mixing parameters x and y . Additionally, comparing the D^0 decay time distribution to that for \bar{D}^0 allows one to measure or constrain the CP -violating (CPV) parameters $|q/p|$ and $\text{Arg}(q/p) \equiv \phi$. This method has been used previously by Fermilab experiments E791 [2] and E831 [3] to search for D^0 - \bar{D}^0 mixing. However, those experiments ran in the 1990’s and reconstructed only a few hundred flavor-tagged $D^0 \rightarrow K^+\pi^-$ decays. Technological advances in vertexing detectors and electronics made since E791 and E831 ran now make a much improved fixed-target experiment possible. Here we estimate the expected sensitivity of such an experiment and compare it to that of the B factory experiments Belle and Babar. Those experiments have reconstructed several thousand signal decays and, using these samples along with those for $D^0 \rightarrow K^+K^-/\pi^+\pi^-$, have made the first observation of D^0 - \bar{D}^0 mixing [4,5]. Although we focus on measuring $x, y, |q/p|$, and ϕ , a much broader charm physics program is possible at a Tevatron experiment.

2. EXPECTED SIGNAL YIELD

We estimate the signal yield expected by scaling from two previous fixed-target experiments, E791 at Fermilab and $HERA-B$ at DESY. These experiments had center-of-mass energies and detector geometries similar to those that a charm experiment at the Tevatron would have.

2.1. Scaling from $HERA-B$

$HERA-B$ took data with various trigger configurations. One configuration used a minimum bias trigger, and from this data set the experiment reconstructed 61.3 ± 13 D^* -tagged “right-sign” $D^0 \rightarrow K^-\pi^+$ decays in 182×10^6 hadronic interactions [6]. This yield was obtained after all selection requirements were applied. Multiplying this rate by the ratio of doubly-Cabibbo-suppressed to Cabibbo-favored decays $R_D \equiv \Gamma(D^0 \rightarrow K^+\pi^-)/\Gamma(D^0 \rightarrow K^-\pi^+) = 0.380\%$ [7] gives a rate of reconstructed, tagged $D^0 \rightarrow K^+\pi^-$ decays per hadronic interaction of 1.3×10^{-9} . To estimate the sample size a Tevatron experiment would reconstruct, we assume the experiment could achieve a similar fractional rate. If the experiment ran at an interaction rate of 7 MHz (which was achieved by $HERA-B$ using a two-track trigger configuration), and took data for 1.4×10^7 live seconds per year, then it would nominally reconstruct $(7 \text{ MHz})(1.4 \times 10^7)(1.3 \times 10^{-9})(0.5) = 64000$ flavor-tagged $D^0 \rightarrow K^+\pi^-$ decays per year, or 192000 decays in three years

of running. Here we have assumed a trigger efficiency of 50% relative to that of *HERA-B*, as the trigger would need to be more restrictive than the minimum bias configuration of *HERA-B*.

2.2. Scaling from E791

Fermilab E791 was a charm hadroproduction experiment that took data during the 1991-1992 fixed target run. The experiment ran with a modest transverse-energy threshold trigger, and it reconstructed 35 D^* -tagged $D^0 \rightarrow K^+\pi^-$ decays in 5×10^{10} hadronic interactions [2]. This corresponds to a rate of 7×10^{-10} reconstructed decays per hadronic interaction. Assuming a future Tevatron experiment achieves this fractional rate, one estimates a signal yield of (7 MHz)(1.4×10^7)(7×10^{-10}) = 69000 per year, or 207000 in three years. This value is similar to that obtained by scaling from *HERA-B*. We have assumed the same trigger+reconstruction efficiency as that of E791, for lack of better knowledge. We note that E791 had an inactive region in the middle of the tracking stations where the π^- beam passed through, and a future Tevatron experiment could avoid this acceptance loss. We do not include any improvement for this in our projection.

3. COMPARISON WITH THE *B* FACTORIES

We compare these yields with those that will be attained by the *B* factory experiments after they have analyzed all their data. The Belle experiment reconstructed 4024 D^* -tagged $D^0 \rightarrow K^+\pi^-$ decays in 400 fb^{-1} of data [8], and it is expected to record a total of 1000 fb^{-1} when it completes running. This integrated luminosity corresponds to 10060 signal events.

The Babar experiment reconstructed 4030 tagged $D^0 \rightarrow K^+\pi^-$ decays in 384 fb^{-1} of data [4], and the experiment recorded a total of 484 fb^{-1} when it completed running in early 2008. Thus the total Babar data set corresponds to 5080 signal events. Adding this to the estimated final yield from Belle gives a total of 15100 $D^0 \rightarrow K^+\pi^-$ decays. This is less than 8% of the yield estimated for a Tevatron experiment in three years of running.

The KEK-B accelerator where Belle runs is scheduled to be upgraded to a “Super-*B*” factory running at a luminosity of $\sim 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ [9]. There is also a proposal to construct a Super-*B* factory in Italy near the I.N.F.N. Frascati laboratory [10]. An experiment at either of these facilities would reconstruct very large samples of $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+\pi^-$ decays, and in fact the resulting sensitivity to x'^2 and y' may be dominated by systematic uncertainties. This merits further study. We note that the systematic errors obtained at a future Tevatron experiment are expected to be smaller than those at an e^+e^- collider experiment, due to the superior vertex resolution and π/K identification possible with a forward-geometry detector.

4. COMPARISON WITH LHCb

The LHCb experiment has a forward geometry and is expected to reconstruct $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+\pi^-$ decays in which the D^* originates from a *B* decay. The resulting sensitivity to mixing parameters x'^2 and y' has been studied in Ref. [11]. This study assumes a $b\bar{b}$ cross section of $500 \mu\text{b}$ and estimates several unknown trigger and reconstruction efficiencies. It concludes that approximately 58000 signal decays would be reconstructed in 2 fb^{-1} of data, which corresponds to one year of running. This yield is similar to that estimated for a Tevatron experiment. However, LHCb’s trigger is efficient only for *D* mesons having high p_T , i.e., those produced from *B* decays. This introduces two complications:

1. some fraction of prompt $\bar{D}^0 \rightarrow K^+\pi^-$ decays will be mis-reconstructed or undergo multiple scattering and, after being paired with a random soft pion, will end up in the $D^0 \rightarrow K^+\pi^-$ sample fitted for x'^2 and y' . As the production rate of prompt *D*’s is two orders of magnitude larger than that of *B*’s, this component may be non-negligible and thus would need to be well-understood when fitting.
2. to obtain the D^* vertex position (i.e., the origin point of the D^0), the experiment must reconstruct a $B \rightarrow D^*X$ vertex, and

the efficiency for this is not known. Monte Carlo studies indicate it is 51% [11], but there is uncertainty in this value.

The LHCb study found that, for $N_{K^+\pi^-} = 232500$, a signal-to-background ratio (S/B) of 0.40, and a decay time resolution (σ_t) of 75 ps, the statistical errors obtained for x'^2 and y' were 6.4×10^{-5} and 0.87×10^{-3} , respectively. These values are less than half of those that we estimate can be attained by the B factories by scaling current errors by $\sqrt{N_{K^+\pi^-}}$: $\delta x'^2 \approx 14 \times 10^{-5}$ and $\delta y' \approx 2.2 \times 10^{-3}$. As the signal yield, S/B , and σ_t of a future Tevatron experiment are similar to those for LHCb, we expect that similar errors for x'^2 and y' can be attained.

To check these estimates, we have done a ‘‘toy’’ Monte Carlo (MC) study to estimate the sensitivity of a Tevatron experiment. The results obtained are similar to those of LHCb: for $N_{K^+\pi^-} = 200000$, $S/B = 0.40$, $\sigma_t = 75$ ps, and a minimum decay time cut of $0.5 \times \tau_D$ (to reduce combinatorial background), we find $\delta x'^2 = 5.8 \times 10^{-5}$ and $\delta y' = 1.0 \times 10^{-3}$. These errors are the RMS's of the distributions of residuals obtained from fitting an ensemble of 200 experiments. A typical fit is shown in Fig. 1.

5. GLOBAL FIT FOR CPV PARAMETERS

If we assume the $\delta x'^2$ and $\delta y'$ errors obtained in our toy MC study (which are close to the values obtained in the LHCb study), we can estimate the resulting sensitivity to CPV parameters $|q/p|$ and ϕ . The first parameter characterizes CPV in the mixing of D^0 and \bar{D}^0 mesons, while the second parameter is a phase that characterizes CPV resulting from interference between an amplitude with mixing and a direct decay amplitude. In the Standard Model, $|q/p|$ and ϕ are essentially 1 and 0, respectively; a measurable deviation from these values would indicate new physics.

To calculate the sensitivity to $|q/p|$ and ϕ , we do a global fit of eight underlying parameters to 28 measured observables. The fitted parameters are x and y , strong phases $\delta_{K\pi}$ and $\delta_{K\pi\pi}$, R_D , and CPV parameters A_D , $|q/p|$ and ϕ . Our fit is analogous to that done by the Heavy Flavor Av-

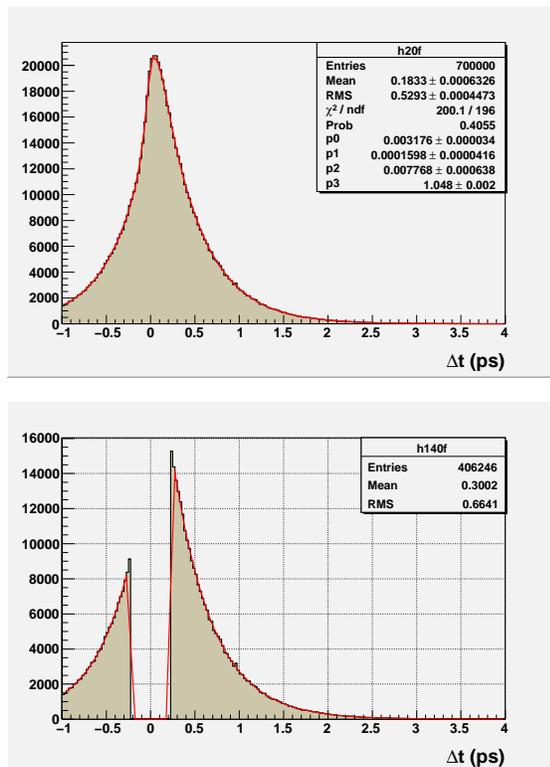


Figure 1. Monte Carlo $D^0 \rightarrow K^+\pi^-$ decay time distributions without (top) and with (bottom) a minimum decay time cut. Superimposed is the result of a fit. The ratio of signal to background after the $t_{\min} (= \tau_D/2)$ cut is 0.40, and the decay time resolution σ_t is 75 fs.

eraging Group (HFAG) [12]; the only difference is that we reduce the errors for x'^2 and y' according to our toy MC study, and we also reduce the error for y_{CP} by a similar fraction. This latter parameter is measured by fitting the decay time distribution of $D^0 \rightarrow K^+K^-/\pi^+\pi^-$ decays, which would also be triggered on and reconstructed by a Tevatron charm experiment.

The results of the fit are plotted in Fig. 2b. The figure shows two-dimensional likelihood contours for $|q/p|$ and ϕ ; for comparison, the analogous HFAG plot is shown in Fig. 2a. One sees that a future Tevatron experiment would yield a very substantial improvement.

6. SUMMARY

In summary, we note the following and conclude:

- $D^0\text{-}\bar{D}^0$ mixing is now established, and attention has turned to the question of whether there is CPV in this system.
- Technical advances in detectors and electronics made since the last Fermilab fixed-target experiments ran would make a new experiment much more sensitive to mixing and CPV effects. Silicon strips and pixels for vertexing are well-developed, and detached-vertex-based trigger concepts and prototypes exist (e.g., *HERA-B*, CDF, BTeV, LHCb).
- Such an experiment would have substantially better sensitivity to mixing and CPV than all Belle and Babar data together will provide. The Tevatron data should have less background than LHCb data. Systematic uncertainties may also be less than those of the B factory experiments and LHCb.
- The Tevatron and requisite beamlines are essentially available.
- Such an experiment could help untangle whatever signals for new physics appear at the Tevatron or LHC.

Recently, a working group has formed to study the physics potential of a charm experiment at the Tevatron in more detail. Information about this working group and its results can be obtained at <http://www.nevis.columbia.edu/twiki/bin/view/FutureTev/WebHome>.

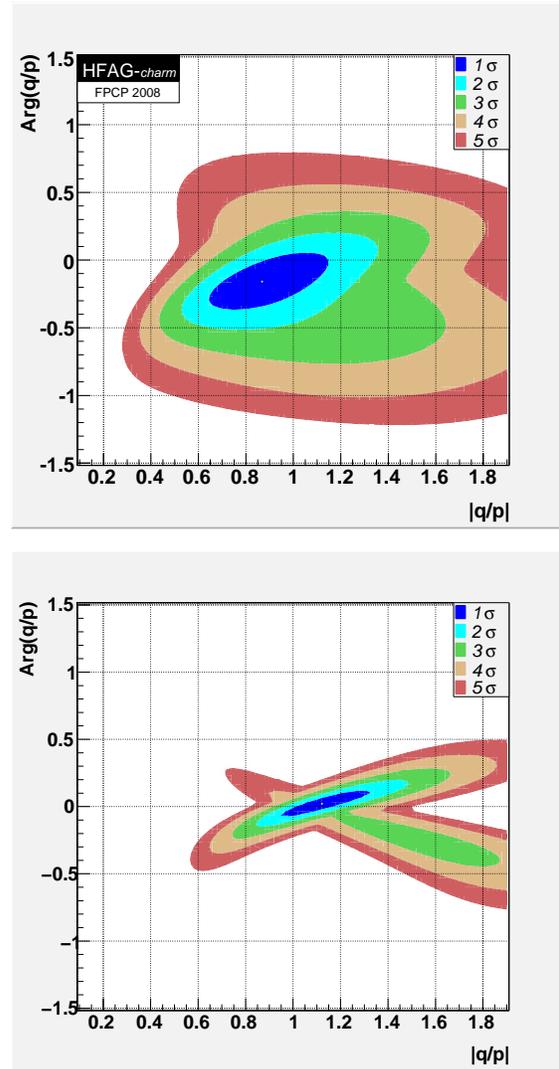


Figure 2. $|q/p|$ versus ϕ likelihood contours resulting from a global fit to measured observables (see text). Top: data after FPCP 2008, from the Heavy Flavor Averaging Group [12]. Bottom: after three years of running of a Tevatron charm experiment.

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