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# CP Violation, Mixing and Rare Decays at the Tevatron Now and in Run II

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# $CP$ Violation, Mixing and Rare Decays at the Tevatron Now and in Run II


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**Abstract.** We review the status of current $B$ mixing and $CP$ violation measurements from the Fermilab Tevatron. With the existing data sample, the CDF collaboration has made competitive measurements of $B_d^0$ mixing; set limits on $B_s^0$ mixing; and has begun a direct search for $CP$ violation in the $B$ system through the decay $B^0/\overline{B^0} \rightarrow J/\psi K_s^0$. The prospects for future $b$ measurements at the Tevatron, including $CP$ violation, $B_s^0$ mixing and rare decay searches are discussed.


## I INTRODUCTION

Over the course of the last 10 years, the $B$-physics program at the Tevatron has been very rich. Beginning with the observation of exclusive $B$ decays in the 1980s, the program really blossomed with the introduction of silicon microvertex detectors in the 1990s.

The goal of this paper is to outline some of the measurements of the $B$ quark sector performed at the Tevatron. The CDF and DØ experiments have learned a great deal about making these measurements in the challenging environment of a hadron collider. With forthcoming accelerator and detector upgrades, the future prospects for new and more precise measurements of $CP$ violation, $B_s^0$ mixing and rare $B$ decays is very bright.

The paper is outlined as follows. After a brief introduction to the CKM matrix, we give an overview of the Run I measurements of $B_d^0$ mixing and the $CP$ violation parameter $\sin 2\beta$. After in introduction to the accelerator and detector upgrades for Run II, we outline the experimental sensitivity for $CP$ violation parameters, $B_s^0$ mixing and rare $B$ decays in Run II.

## II THE CKM MATRIX

The Cabibbo-Kobayashi-Maskawa matrix $V_{CKM}$ is a unitary matrix which rotates the electroweak eigenstates into the mass eigenstates:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where the expansion in terms of $\lambda = \sin\theta_C$, the sine of the Cabibbo angle, is known as the Wolfenstein parameterization. Of the four free parameters, two: $\lambda$ and $A$ are well-measured, with relative errors of $\delta\lambda/\lambda \simeq 1\%$ and $\delta A/A \simeq 4\%$ [1]. The other two, $\rho$ and $\eta$ are rather weakly constrained through indirect measurement. These constraints rely heavily upon parameters which are not will constrained theoretically. The ongoing goal for $B$ physics measurements has been and will be to further constrain the CKM matrix.

Imposing the condition of unitarity, $V^\dagger V = 1$, yields a number of relations between entries of the matrix. The most useful of these relations is:

$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0. \tag{1}$$

This condition can be displayed graphically as a triangle in the imaginary ($\rho$-$\eta$) plane. Dividing the base by $V_{cd}V_{cb}^*$ to make it unit length leaves the "unitarity triangle" which is shown in Figure 1.

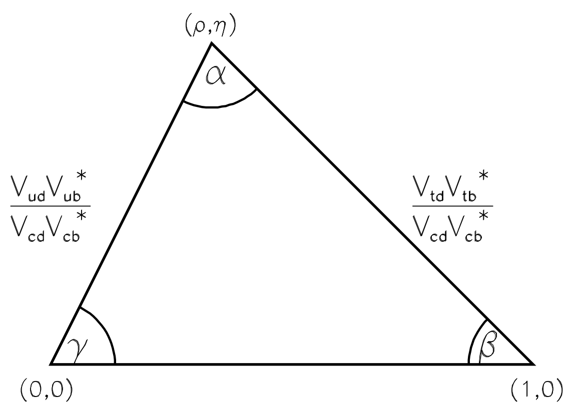


**FIGURE 1.** The unitarity triangle indicating the relationship between CKM elements $\rho$ and $\eta$.

The program we describe here is part of an ongoing effort to measure the sides and and angles of the unitarity triangle in an effort to overconstrain the CKM matrix, and hence, test the Standard Model.

## III OVERVIEW: $B$ PHYSICS AT THE TEVATRON

The Fermilab Tevatron offers some unique opportunities in $b$-physics which are not available elsewhere. The proton-antiproton collisions at $\sqrt{s} = 1.8\,\text{TeV}$ create

$b\bar{b}$ pairs with a cross section of approximately $100\,\mu$b. The $b$ quarks can hadronize into all species, including $b$-baryons, and $B_s^0$ and $B_c$ mesons.

With an inelastic $p\bar{p}$ cross section which is approximately 1000 times larger than the $b\bar{b}$ cross section, it has so far been necessary to trigger on leptons from the $B$-hadron decays. The most common trigger paths are: $b \to \ell\nu c$ and $b \to \psi X$, $\psi \to \mu^+\mu^-$. The signal-to-noise can be improved significantly by constructing a detector that has excellent mass resolution and that can exploit the long $b$ lifetime ($\tau_B = 1.564 \pm 0.014\,$ps, $c\tau_B = 469\,\mu$m [1].) Outer tracking detectors along with a solenoid magnetic field offer good transverse momentum ($p_T$) and therefore good mass resolution. Silicon microvertex detectors can resolve tracks originating from long lived particles with high efficiency.

Even though the center of mass energy of the $p\bar{p}$ system is very large, the $B$ hadron spectrum is relatively soft. For the decay $B \to \psi K_S^0$ with a $2\,$GeV/c transverse momentum requirement on both muons, the mean $p_T$ of the $B$ is about $10\,$GeV/c. This implies that tracking at low $p_T$ (few hundred MeV) and forward tracking are both important aspects to $b$-physics at the Tevatron.

# IV RUN I MEASUREMENTS

In the period 1992-1996, the CDF and DØ collaborations measured approximately $110\,\text{pb}^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,$TeV. In the following sections, we present a few of the many measurements which have come from these data samples. The large number of measurements of $B$ cross sections, branching ratios, masses and lifetimes have been made at the Tevatron but will not be included here.

## A $B_d^0$ Mixing

$B^0/\overline{B^0}$ mixing proceeds through box diagrams involving the top quark. The CKM elements $V_{tb}$ and $V_{td}$ come into play as the tops are exchanged in the box. The element $V_{td}$ contains $\rho$ and $\eta$ and, as a consequence of this, $B_d^0$ mixing is sensitive to the length of one side of the unitarity triangle.

CDF has performed a number of measurements of time dependent $B_d^0$ mixing. In order to make these measurements, the following items are required:

1. trigger on $b\bar{b}$ events
2. tag the flavor of the $B^0/\overline{B^0}$ at the time of production
3. measure the lifetime of the $B^0/\overline{B^0}$
4. tag the flavor of the $B^0/\overline{B^0}$ at the time of decay

For these analyses, the trigger path takes advantage of the $b \to \ell\nu c$ decays where an energetic lepton can be identified. In addition, the charge of this lepton provides the tag of the flavor of the $B$ at the time of decay. Corrections must be applied for fake leptons and leptons from sequential $b \to c \to \ell \nu s$ decays. A precision measurement of the decay length in the transverse plane is made using information from the silicon microvertex detector. This is converted to a $B$ lifetime with an approximate correction for the velocity ($\beta\gamma$) of the $B$.

To measure mixing, the flavor of the $B$ meson (that is, whether it contains a $b$-quark or a $\bar{b}$-quark) must be identified ("tagged") at the time of production and at the time of decay. Since tagging algorithms are far from perfect, the true asymmetry is "diluted" by mistagging $B^0/\overline{B^0}$: $A_{obs} = DA_{true}$, where $A_{obs}$ is the observed asymmetry and $D$ is the "tagging dilution", defined as the asymmetry between the number of correct tags and incorrect tags: $D = (N_R - N_W)/(N_R + N_W)$ where $N_R(N_W)$ = number of correct (incorrect) tags. The dilution is related to the mistag rate in the following way: $D = 1 - 2w$, where $w$ is the total fraction of incorrect tags.

The mixing analyses differ in two respects: first is the method used to further isolate the triggered $b\bar{b}$ events from background and second is the method used to tag the flavor of the $B$ at the time of production.

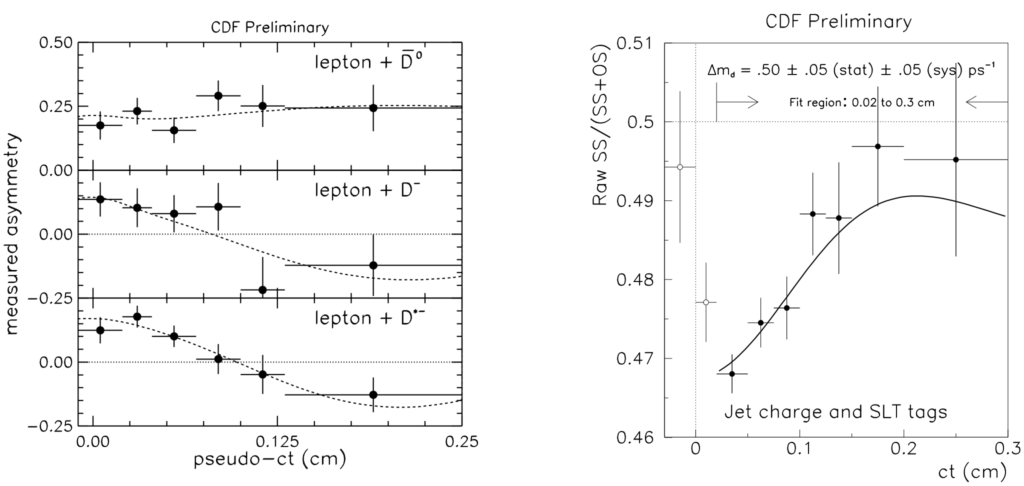


**FIGURE 2.** Time dependent $B^0/\overline{B^0}$ mixing as measured from: **Left:** $B^0/\overline{B^0} \to \ell^{\pm}\nu D^{\mp}(D^{*\mp})$. The top plot shows the $B$-$\pi$ charge correlation in the $B^{\pm}$ sample, where no mixing takes place. The middle and bottom plots show the correlation for $B^0/\overline{B^0}$ events, where the oscillatory behavior can be seen. **Right:** an inclusive lepton sample using both jet charge and soft lepton tagging. The $B$ events are identified with a secondary vertex. Explicit charge/neutral $B$ separation is not performed.

Figure 2 shows the CDF measurement of $B_d^0$ mixing using the same-side tagging method. In this analysis, lepton triggered events are reconstructed in the $\ell D(D^*)$ mode. The flavor of the $B$ at the time of decay is established from the charm ($D$) decay, while the flavor at production is inferred from the charge correlation of tracks near the $B$ hadron with the flavor of the $b$-quark. This "same-side" correlation may arise through the fragmentation process or through excited ($B^{**}$) states [2].

Also shown in Figure 2 is the mixing result using jet charge and soft lepton flavor tagging algorithms. Here, the flavor of the $B$ at the time of production is inferred from the second $B$ hadron in the event. This is known as "opposite-side" tagging. The problem with opposite side tagging is that quite often (~50% of the time) the second $B$ hadron is boosted forward in the lab frame, outside the acceptance of the detector. In addition, if the second $B$ hadronizes as a $B_d^0$ or a $B_s^0$, then mixing can further confuse the tag. In the jet charge/soft lepton analysis, there is no explicit $D$ reconstruction. The $B$ sample is identified by requiring a secondary vertex to be reconstructed in conjunction with the trigger lepton. Corrections are required for direct $c\bar{c}$ production and sequential $b \to c \to \ell\nu s$ decays.

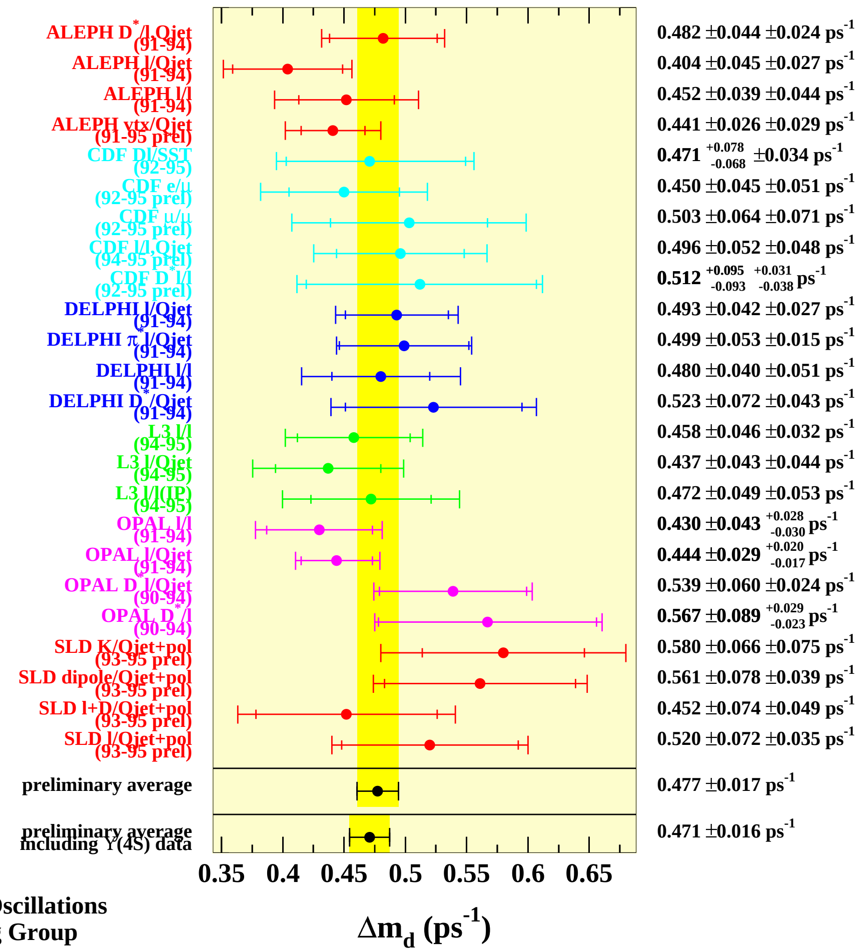


**FIGURE 3.** World average $\Delta m_d$ measurements as of the summer of 1998.

Figure 3 shows the status of $B_d^0$ mixing measurements as of the Summer of 1998 [3]. As can be seen from the plot, the measurements made by CDF (some of which are not discussed in detail here) are competitive with those from LEP and SLD. The world average value is $\Delta m_d = 0.471 \pm 0.016\,\mathrm{ps}^{-1}$.

## B $\sin 2\beta$

$CP$ violation manifests itself as an asymmetry in the decay rate of particle versus antiparticle. In the case of $B^0/\overline{B}^0 \rightarrow \psi K^0_S$:

$$A_{CP} = \frac{N(\overline{B^0} \rightarrow \psi K^0_S) - N(B^0 \rightarrow \psi K^0_S)}{N(\overline{B^0} \rightarrow \psi K^0_S) + N(B^0 \rightarrow \psi K^0_S)}$$

which can be either a time dependent or time-integrated quantity. In the Standard Model, the $CP$ asymmetry in this mode is proportional to $\sin 2\beta$: $A_{CP}(t) = \sin 2\beta \times \sin(\Delta m t)$, where the second term is the time-dependent evolution of $B^0/\overline{B^0}$ mixing. The magnitude of the $CP$ violation term shows up as an amplitude of the mixing term.

Integrating over time, the statistical error on $\sin 2\beta$ can be written as: $\delta \sin(2\beta) \approx \frac{1+x_d^2}{x_d} \frac{1}{\sqrt{\epsilon \mathcal{D}^2 S}} \sqrt{\frac{S+B}{S}}$, where $\epsilon$ is fraction of events which can be tagged (the "tagging efficiency") and $\mathcal{D}$ is the dilution. The quantity $x_d$ is the $B^0/\overline{B^0}$ mixing parameter, $x_d = \Delta m_d/\Gamma$, where $\Delta m_d$ is the mass difference between the heavy and light $B$ meson states and $\Gamma = \hbar/\tau$ is the average lifetime of the states. The signal ($S$) and background ($B$) comprise the sample of $N$ total events, $N = S + B$. In order to minimize the statistical uncertainty in the measurement, the term $\epsilon \mathcal{D}^2$ must be maximized. The dilution is the crucial factor in this equation as it comes in as $\mathcal{D}^2$. This is true because a mistagged event not only is absent from the correct tagging bin, it is also present in the incorrect tagging bin.

CDF has made a direct measurement of the quantity $\sin 2\beta$ using 200 $B \rightarrow J/\psi K^0_s$ decays where both muons are reconstructed in the silicon microvertex detector. The flavor of the $B$ meson at the time of production is measured using same-side tagging. The advantage of using events with well-measured lifetime is that the time-dependent analysis utilizes more information on an event-by-event basis than does the time integrated analysis. As stated above, the asymmetry is of the form: $A_{CP}(t) = \sin 2\beta \times \sin(\Delta m t)$, so the asymmetry versus lifetime is a sine wave with frequency $\Delta m$ and amplitude $\sin 2\beta$. Most of the background is from prompt $J/\psi$ production. Since the $B$ vertex in the $J/\psi K^0_s$ decay is defined by the muons from the $J/\psi$, backgrounds from prompt $J/\psi$ production look like short-lived $B$ decays. At low lifetime, the asymmetry is small. At longer lifetime, the signal-to-noise is much greater and the asymmetry is larger. Overall, the time dependent analysis offers about a 30% reduction in $\delta(\sin 2\beta)$ relative to the time-integrated analysis for a given sample of $B$ decays.

The analysis involves an unbinned likelihood fit in which the events are weighed depending upon their mass, lifetime and tag. Corrections are made for the intrinsic charge asymmetry of the detector. The dilution is required as an external input and extracted from the $\ell D$ mixing analysis with the help of Monte Carlo. The same side tagging dilution for $B \rightarrow J/\psi K^0_s$ decays is measured to be $\mathcal{D} = 0.166 \pm 0.018(\text{stat.}) \pm 0.013(\text{syst.})$ Combining this with the measured asymmetry results in:

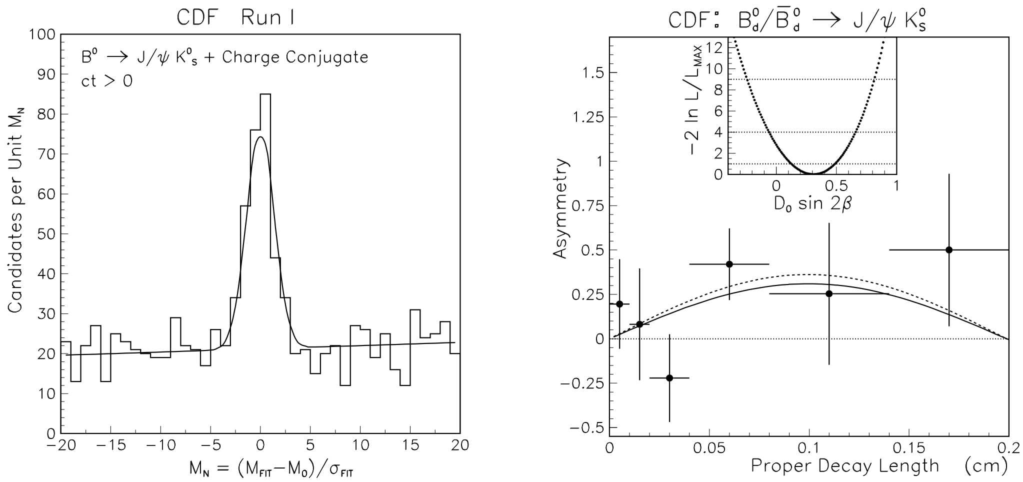


**FIGURE 4. Left:** Normalized mass distribution ($(M_{fit} - M_B)/\sigma_{fit}$) for the fully reconstructed $B \to J/\psi K^0_s$ decay mode. There are 200 events in the mass peak. **Right:** The time dependent asymmetry as measured from same-side tagging. The solid curve represents the result of the full unbinned likelihood fit, the dashed curve is a simple fit to the points. The amplitude of the sine curve is $D \sin 2\beta$.

$\sin 2\beta = 1.8 \pm 1.1\,(\text{stat.}) \pm 0.3(\text{syst.})$ [4]. The error is dominated by the statistical uncertainty. The dominant systematic uncertainty arises from the error in the dilution.

## V TEVATRON RUN II

In February of 1996, the Fermilab Tevatron completed "Run I" in which both the CDF and DØ detectors recorded approximately $110\,\text{pb}^{-1}$ of integrated luminosity. For the upcoming "Run II", the accelerator complex will be upgraded significantly with the construction of two new components: the Main Injector and the Recycler Ring. The instantaneous luminosity is expected to reach $\mathcal{L} = 1 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ with a 396 ns bunch spacing and eventually improve to $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ with a 132 ns bunch spacing. The integrated luminosity for Run II is anticipated to be $2\,\text{fb}^{-1}$ in two years of running.

## VI DØ AND CDF UPGRADES

Both experiments are undergoing significant upgrades in order to take advantage of the major increase in luminosity foreseen for Run II. The scope of these upgrades as they apply to the $b$-physics program will be discussed here.

For $b$-physics at a hadron collider, the most important aspects of the detector are the microvertex detector, tracking chamber and high-rate trigger and data acquisition system. Additionally, it is important to be able to accurately and quickly identify leptons ($e$ and $\mu$) for triggering.

Both experiments are replacing completely their front-end electronics and trigger systems in order to handle the high event rates of Run II. The triggers will be pipelined and multi-staged, so that the lower trigger levels can process incoming events while higher level trigger decisions are made on previous events.

Additionally, both experiments are replacing their tracking systems. DØ is installing a 2T superconducting solenoid magnet which will surround a 4 layer silicon microvertex detector and a scintillating fiber tracker. The microvertex detector will include disks for forward tracking. The fiber tracker will cover out to 1.7 units of pseudorapidity ($\eta$) [5].

CDF is building a new gas-wire drift chamber to replace the existing central tracking chamber. The drift chamber will be able to perform particle identification using specific ionization ($dE/dx$.) A new silicon microvertex detector is being constructed. Additional strips (located cylindrically between drift chamber and the inner silicon strips) will be installed for forward tracking. The readout chip for the silicon system is a custom chip which will allow for simultaneous digitization of data from a previous event while acquiring data into the pipeline on the current beam crossing. This "deadtimeless" mode makes way for a trigger based upon the two-dimensional distance of closest approach (impact parameter) of tracks to the interaction point. The impact parameter information in real-time opens the possibility of triggering on $B$ hadrons decaying to all-hadronic final states through displaced tracks [6].

## A "Beyond the Baseline"

In addition to the baseline detector upgrades for Run II, both detectors are now proposing additional upgrades for Run II which would significantly enhance the capabilities for measurements in the $B$ sector.

DØ is proposing to add silicon vertex trigger which would utilize information from the silicon microvertex detector to look for tracks with displaced vertices. This trigger would also improve the momentum resolution of the existing track-trigger which is based upon the fiber system. As discussed above, a trigger based upon microvertex tracking information opens up a number of possibilities for for triggering on hadronic $b$ decays.

CDF is proposing to add two additional detector elements [7]:

1. A time-of-flight system with 100 ps timing resolution, able to separate $\pi$ and $K$ at $2\sigma$ or better for $p_T < 1.6\,\mathrm{GeV/c}$;

2. An addition layer of silicon ("Layer 00") which would be mounted onto the Tevatron beam-pipe, with an active region 1.6 cm from the beamline. This extra layer of silicon would improve the impact parameter resolution by almost

a factor of two for tracks which pass through additional hybrid material in the outer silicon layers.

As will be seen in the sections below, these two projects would lead to drastic improvements in the $B$ physics potential of the Run II detector.

# VII RUN II $B$ PHYSICS

## A $\sin 2\beta$

The expectations for our reach in $\sin 2\beta$ in Run II can be a direct extrapolation from existing measurements of tagging dilutions and event yields.

Improvements over the Run I yield are expected from $a$) improved muon coverage and $b$) an improved signal-to-noise from the additional microvertex detector coverage. Based upon the improvements listed here and the Run I data sample shown in Figure 4, the Run II yield estimate is 10,000 events in $2\,\mathrm{fb}^{-1}$. Studies indicate that this sample could be as much as doubled by triggering on $\psi \to e^+e^-$ in addition to lowering the dimuon trigger $p_T$ thresholds from 2.0 GeV/c to 1.5 GeV/c [6].

Given this large sample of events, the statistical reach in $\sin 2\beta$ will depend largely on the "effective tagging efficiency", $\epsilon\mathcal{D}^2$, as outlined earlier. The existing CDF measurement of $\sin 2\beta$ uses only one tagging algorithm, same-side tagging. Work is ongoing to incorporate information from lepton tagging and jet charge tagging into the Run I analysis.

**TABLE 1.** "Effective tagging efficiencies" for different flavor tagging methods as measured by CDF. The last two columns show the the expected improvements due to the detector upgrade. Many of the increases are due to an improved acceptance.

| tagger | $\epsilon\mathcal{D}^2$ [%] measured Run I | $\epsilon\mathcal{D}^2$ [%] expected Run II | Relevant upgrade |
|---|---|---|---|
| Same Side $\pi$ | $1.8 \pm 0.4$ | $2.0^\dagger$ | new tracking |
| Soft $\mu$ | $0.72 \pm 0.12$ | 1.0 | extend coverage |
| Soft $e$ | $0.35 \pm 0.04$ | 0.7 | new tracking |
| Jet Charge | $0.78 \pm 0.15$ | 3.0 | new tracking |
| Opp.Side Kaon | – | 2.4 | Time-Of-Flight |
| All combined | 3.7 | 6.7 (9.1) | |

$^\dagger$ This number improves further with Time-of-Flight.

CDF has measured the tagging efficiencies for several types of tagging methods in the context of $B^0/\overline{B^0}$ mixing. Table 1 shows measured and expected tagging efficiencies, along with the relevant detector upgrades which will improve the efficiencies.

For Run II, the estimated error on $\sin 2\beta$ for CDF (using $\epsilon\mathcal{D}^2 = 6.7\%$) is approximately $\delta \sin 2\beta \simeq 0.08$. This error will improve significantly if triggering on $\psi \to e^+e^-$ and lower muon $p_T$ thresholds are achieved with reasonable efficiency. A time-of-flight system would significantly improve the effective tagging efficiency by introducing a "kaon" tag. It has been shown that tagging charged kaons from the $b$ decays is a very powerful tagging method, due to the cascade $b \to c \to s$ decay [8]. The $dE/dx$ particle identification of CDF does not offer sufficient $\pi$-$K$ separation at low momenta ($p_T < 1.5\,\mathrm{GeV/c}$) to tag efficiently with kaons. The addition of a time-of-flight system would significantly enhance this ability and effectively increase the statistics by 35%.

The Run II measurement of $\sin 2\beta$ will remain statistics limited. The dominant systematic uncertainty will again arise from the uncertainty in the tagging dilution. The dilutions for this measurement are calibrated from the exclusive decays $B^\pm \to J/\psi K^\pm$ and $B^0 \to J/\psi K^{*0}$. Given that the uncertainty on the dilution arises from the statistics of the calibration samples, the relative size of the statistical versus systematic errors in $\sin 2\beta$ will remain roughly constant.

Estimates from DØ suggest an error on $\sin 2\beta$ in the range of $0.12 - 0.15$ in $2\,\mathrm{fb}^{-1}$.

## B $A_{CP}$ in $B_d^0 \to \pi^+\pi^-$

$CP$ violation in the decay $B^0/\overline{B^0} \to \pi^+\pi^-$ is related to the angle $\alpha$ in the unitarity triangle. This all hadronic decay mode is very challenging at a hadron collider. Due to the small branching ratio ($< 8.4 \times 10^{-6}$ [9]) we know that a significant sample can not be reconstructed opposite a $b \to \ell$ trigger.

CDF is implementing a secondary vertex trigger at Level 2 to separate hadronic $B$ decays from inelastic (prompt) background. The information from the track trigger processor is combined with hits from the microvertex detector to measure the impact parameter of the tracks. The impact parameter resolution of this device is approximately $35\,\mu$m and the impact parameter information will be supplied to the trigger decision processor in less than $15\,\mu$s. This device requires beam position stability both during the store and from store-to-store. Real time beam position information will be fed back to the accelerator so that the position of the interaction region can be maintained over the course of the store.

Based upon existing data, it is estimated that an impact parameter cut of $100\,\mu$m will yield a rejection factor of about 1000. The bandwidth challenge for the trigger is at Level 1, where no impact parameter information is available. Here a two-track trigger with kinematic cuts will yield a rate of 16 kHz. That rate is reduced to 20 Hz at Level 2 with the impact parameter trigger.

After triggering on the $B \to$ two-track final state, the $B_d^0 \to \pi^+\pi^-$ final state must be isolated from the physics backgrounds from $B_d^0 \to K\pi$, $B_s^0 \to K\pi$ and $B_s^0 \to KK$. The mass resolution of the tracking system ($20\,\mathrm{MeV/c}^2$ for $B_d^0 \to$

**TABLE 2.** Comparison of experimental uncertainties on $\sin 2\beta$ and $\sin 2\alpha$ from the upcoming generation of experiments. The anticipated results are listed for one year of running at design luminosity. Please note that there are a number of caveats and assumptions which go into each of these projections. The numbers are tabulated here only to give the reader a feel for not only how well each of the experiments expect to ultimately perform, but to also show the complementarity of the different experiments.

| | | BELLE [10] | BaBar [11] | Hera-B [12] | DØ | CDF |
|---|---|---|---|---|---|---|
| $\int \mathcal{L}dt\,(\mathrm{fb}^{-1})$ | | 100 | 30 | 100 | 1 | 1 |
| $\mathrm{N}(B_d^0 \to \psi K_S^0)$ | | 2000 | 1100 | 1500 | 4k | 5k |
| $\delta(\sin 2\beta)$ | $\psi K_S^0$ | 0.080 | 0.098 | 0.13 | 0.20 | 0.10 |
| | all modes | 0.062 | 0.059 | 0.12 | 0.20 | 0.10 |
| $\mathrm{N}(B_d^0 \to \pi^+\pi^-)$ | | 650 | 350 | 800 | – | 4.6k |
| $BR(B_d^0 \to \pi^+\pi^-)^*$ $(\times 10^{-5})$ | | 1.3 | 1.2 | 1.5 | – | 0.5 |
| $\delta(\sin 2\alpha)^\dagger$ | $\pi^+\pi^-$ | 0.147 | 0.20 | 0.16 | – | 0.12 |
| | all modes | 0.089 | 0.085 | 0.16 | – | 0.12 |

* Assumed branching ratio.

† Assuming that contamination from penguin decays can be unfolded.

$\pi^+\pi^-$) is not sufficient to isolate the signal from these backgrounds. In particular, the $B_s^0 \to KK$ final state reflects directly under the $B_d^0 \to \pi^+\pi^-$ mass peak when the two kaons are assumed to be pions.

To further isolate the $B_d^0 \to \pi^+\pi^-$ signal from these physics background, $\pi$-$K$ separation is required. CDF will use $dE/dx$ information from the central tracking chamber to separate the signal from the backgrounds on a statistical (not event-by-event) basis. The system will yield $> 1\sigma$ $\pi$-$K$ separation for $p_T > 2\,\mathrm{GeV/c}$. The proposed time-of-flight system, although very useful for flavor tagging, will not be capable of $\pi$-$K$ separation at these higher momenta.

The yield estimate is $9k$ $B_d^0 \to \pi^+\pi^-$ events in $2\,\mathrm{fb}^{-1}$. Including all possible tagging modes (*i.e.* using the $\epsilon\mathcal{D}^2 = 6.7\%$ from Table 1), the estimated error on the $CP$ asymmetry in $B_d^0 \to \pi^+\pi^-$ is approximately 0.10. If the contribution from the penguin decays were small, then the $CP$ asymmetry measured in this mode would be $\sin 2\alpha$. The exact precision on $\sin 2\alpha$ will depend upon how well the contamination from the penguin mode can be unfolded.

## C Comparing with Projections from Other Experiments

Several experiments will be collecting data in the period 1999-2002. Two $e^+e^-$ $B$-factories at SLAC(BaBar) and KEK(BELLE), as well as a internal target production experiment at HERA(HERA-B) all intend to make many measurements in the $B$ sector, including measurements of $\sin 2\beta$ and $\sin 2\alpha$. Table 2 shows the expected reach of each of these experiments in approximately one year of running at the design luminosity of each machine.

It is interesting to note that although the expected reach is similar for all of the experiments, the Tevatron measurements are in marked contrast to the measurements at BELLE, BaBar and HERA-B. Those experiments will have significantly smaller data samples but significantly better tagging efficiencies. This, along with different modes of production will allow all of these measurements to complement one another. This also points out how crucial flavor tagging is at the Tevatron.

All of these experiments plan a rich physics program beyond the measurements of these two angles of the unitarity triangle. Also, CLEO-III will be running during this period, and will produce a large number of measurements of their own, including information which will help unfold the penguin contributions to $B_d^0 \to \pi^+\pi^-$ [13].

## D Time Dependent $B_s^0$ Mixing

An observation of $B_s^0/\overline{B_s^0}$ mixing would lead to a measurement of the ratio of CKM elements $V_{td}$ and $V_{ts}$ in the following way:

$$\frac{x_s}{x_d} = \frac{(m_{B_s^0}\eta_{QCD}^{B_s^0} B_{B_s^0} f_{B_s^0}^2)}{(m_{B_d^0}\eta_{QCD}^{B_d^0} B_{B_d^0} f_{B_d^0}^2)} \left|\frac{V_{ts}}{V_{td}}\right|^2 = (1.3 \pm 0.2)\left|\frac{V_{ts}}{V_{td}}\right|^2 \tag{2}$$

where $x_i = \Delta m_i/\Gamma_i$ $(i = d, s)$; $m_{B_i}$ are the meson masses; $B_{B_i}$ are $B$ meson bag parameters; $f_{B_i}$ are $B$ meson weak decay constants and $\eta_{QCD}^{B_i}$ are QCD corrections of order unity.

$B_s^0$ mixing will be studied using both semileptonic and fully reconstructed decay modes. Semileptonic decays which include $B_s^0 \to D_s \ell \nu$ and $B_s^0 \to \phi \ell \nu X$ have the advantage of large statistics, but the drawback of the missing neutrino leading to poor $\beta\gamma$ (boost) resolution. CDF has established a limit on $B_s^0$ mixing $\Delta m_s > 5.8\,\mathrm{ps}^{-1}$ at 95% CL) using a sample of 1068 $B_s^0 \to \phi \ell \nu X$ decays with a $B_s^0$ purity of 61%.

For Run II, the proper decay time resolution becomes the limiting factor in semileptonic decays. The ultimate $x_s$ reach through this mode at the Tevatron is approximately 20.

For a measurement of time dependent or time integrated mixing, the flavor of the $B$ hadron must be identified at both the time of production and the time of decay. In the case of $B_s^0 \to D_s X$, the decay of the $D_s$ into $\phi\pi$, $K^*K$ or $K_s^0 K$ uniquely identifies the flavor of the $B_s^0/\overline{B_s^0}$ at the time of decay.

Fully reconstructed decays offer the advantage of much better boost resolution over the semileptonic modes. The drawback is that decay modes without leptons in the final state have not yet been triggered upon (and isolated) at a hadron collider. This means that the $B_s^0 \to D_s\pi(3\pi)$ must be either reconstructed opposite a trigger $B \to \ell$ or else an impact parameter trigger must be used to attempt to separate the all hadronic final state. In either case, the statistics of the fully reconstructed mode will be significantly reduced from the semileptonic modes. However, studies performed by both DØ and CDF have shown that the ultimate reach in $x_s$ will be better for the fully reconstructed mode than it will be for the semileptonic mode.

Figure 5 shows the anticipated reach in time dependent $B_s^0$ mixing using the fully reconstructed modes. The yield estimate is $20k$ events in $2\,\mathrm{fb}^{-1}$. Less certain is the signal-to-noise, so the result is plotted with two different $S{:}N$ assumptions. Using the same tagging strategies as planned for the $\sin 2\beta$ measurement[1], the ultimate reach with the baseline CDF Run II detector is $x_s \simeq 40$, but note the significant improvement in reach when the proposed upgrades (an additional layer of silicon near the beamline and a time-of-flight detector) are included. If these upgrades are approved and included at the beginning of Run II, the ultimate reach in $x_s$ could be as high as 65 [7].

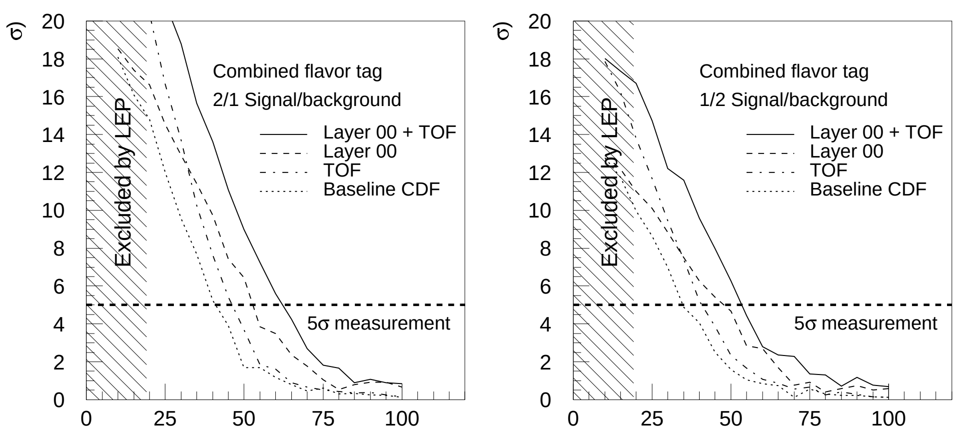


**FIGURE 5.** CDF Run II sensitivity to $B_s^0$ mixing using fully reconstructed $B_s^0 \to D_s\pi(3\pi)$. The plots show the significance of the measurement in $2\,\mathrm{fb}^{-1}$ of data for two different assumptions of $S{:}N$. The sensitivity quoted in the text comes from the point where the curves cross the $5\sigma$ line. For the baseline detector, the reach is in the range $x_s \sim$30-40. With the additional upgrades discussed in the text, this reach is extended to $x_s \sim$55-65.

## E Lifetime Difference

The ultimate reach in time dependent $B_s^0$ mixing in Run II is $x_s \sim$ 40-60. In the event that $x_s$ is larger than this, it will be possible to directly measure two

1) The opposite-side tagging algorithms will have the same dilution for $B_s^0$ as they do for $B_d^0$. This is not the case for same-side tagging because the $B_s^0$ fragmentation chain yields many more kaons the does the fragmentation chain for the $B_d^0$. Without a time-of-flight system, the dilution for same-side tagging is worse ($\mathcal{D} \simeq 5\%$ due to same-side $K^*$ and wrong-sign $\pi$ production) than it is for $B_d^0$. Including the time-of-flight system to reject non-$K$ tracks improves the same-side tagging dilution for $B_s^0$ to $\mathcal{D} = 40\%$.

different lifetime components of a $B_S^H$ (heavy) and $B_S^L$ (light) mass eigenstates in an analogous fashion to the neutral kaon system.

In the Standard Model [15]:

$$\Delta\Gamma_{B_s^0}/\Delta m_{B_s^0} = -\frac{3}{2}\pi\frac{m_b^2}{m_t^2}\frac{\eta_{QCD}^{\Delta\Gamma_{B_s^0}}}{\eta_{QCD}^{\Delta m_{B_s^0}}}, \tag{3}$$

where $\Delta\Gamma = \Gamma_H - \Gamma_L$ is the lifetime difference between the two $CP$ eigenstates. The ratio $\Delta\Gamma_{B_s^0}/\Delta m_{B_s^0}$ contains no CKM elements and the uncertainty on this ratio depends only upon QCD corrections which are of order unity. Therefore, as $\Delta m_s$ ($x_s$) gets larger and becomes inaccessible, the lifetime difference grows and becomes accessible. Based upon the mass of the top quark and measurements in the $B$ system such as $\Delta m_d$ and $V_{ub}$, we expect $x_s$ to be around 20 [16]. Therefore, if in fact $B_s^0$ oscillations can not be resolved directly, it is likely that non-Standard Model effects are playing a roll.

In current event samples, the two main sources of $B_s^0$ decays are the $D_s\ell$ and $\psi\phi$ final states. The $D_s\ell$ sample is expected to be a 50:50 $CP$ even/$CP$ odd mixture. It would be possible to directly fit the lifetime distribution for two lifetime components. CDF has performed such an exercise using approximately 600 $B_s^0 \to D_s\ell\nu$ events. The limit is $\Delta\Gamma/\Gamma < 0.83$ at 95% CL, which translates into a limit on the $B_s^0$ mass difference of $\Delta m_s < 96\,\mathrm{ps}^{-1}$ at 95% CL [17]. With the increased statistics of Run II, this method will become sensitive to $\Delta m_s$ if it is larger than current expectations.

The $B_s^0 \to \psi\phi$ decay mode is expected to be predominantly $CP$ even. A comparison of the lifetime in that mode to the lifetime measured in the inclusive $D_s\ell$ sample would show a difference due to the differing contributions of the short-lived and long-lived components. If the $\psi\phi$ final state is not a pure $CP$ eigenstate, the $CP$ components to that state will be unfolded via a transversity analysis [18]. Then each $CP$ component in $\psi\phi$ can be fit for a lifetime separately. As discussed in the previous section, additional $B_s^0$ decay modes are expected to be included in the Run II analyses.

## F $B_c$

The $B_c$ is an interesting $q\overline{q}'$ system because of the two unequal heavy quark masses. CDF has reported and observation of the $B_c$ in the decay $B_c \to J/\psi\ell\nu$ [19]. The lifetime measurement from this analysis, $\tau(B_c) = 0.46^{+0.18}_{-0.16}(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$ ps indicates a more "charm-like" lifetime for this system than expected. Detailed study of this system will have to await the additional statistics of Run II. Measurement of the $B_c$ production cross section, mass and lifetime are of particular interest.

It should be noted that although $B_c$ decay modes involving the $\psi$ are substantial, the dominant decay mode is expected to be the $c \to s$ transition, giving $B_c \to B_s^0 X$. Given enough statistics, the $B_c$ could become a very powerful flavor tagging tool for $B_s^0$ mixing. As an example, if a sample of $B_c^\pm \to B_s^0\pi^\pm$ could be isolated, the flavor of the $B_s^0$ would be unambiguously tagged at the time of production by the charge of the associated pion from the $B_c$ decay.

## G Radiative Decays

In the absence of long distance effects, $|V_{td}/V_{ts}|$ can be probed via $B \to \rho\gamma$ and $B \to K^*\gamma$. CDF installed a dedicated trigger for radiative $B$ decays for the latter part of Run I. With $23\,\mathrm{pb}^{-1}$ of data taken with this trigger a limit of $BR(B^0 \to K^{*0}\gamma < 2.2 \times 10^{-4}$ was established. If the rates are near Standard Model expectations, approximately 2500 $K^*\gamma$ events should be seen. Additionally, a signal should be seen in the decay mode $B_s^0 \to \phi\gamma$.

Radiative decays detected via photon conversion will also be pursued. The conversion rate is small (few percent) and depends upon the amount material in the inner detector regions. The advantage in using conversions arises from *a*) lower trigger thresholds for electrons versus photons and *b*) much improved $\pi^0$ rejection.

## H Rare $B$ Decays

As in the kaon system, rare decays are sensitive to physics beyond the Standard Model. Both CDF and DØ will be well suited to search for (and likely observe some) of the following rare decays:

- $B^+ \to \mu^+\mu^-K^+$
- $B^0 \to \mu^+\mu^-K^{*0}$
- $B^0 \to \mu^+\mu^-$
- $B_s^0 \to \mu^+\mu^-$.
- $B_s^0 \to e^+\mu^-$

Good muon coverage and mass resolution enhance the reach of searches in the dimuon modes. Based upon Standard Model rates, it is likely that the decay modes $\mu^+\mu^-K^+$ and $\mu^+\mu^-K^{*0}$ will be observed. The Standard Model expectations for $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ are well below the expected Run II reach. This means that any signal seen in these modes will be an immediate signal of new physics.

# VIII CONCLUSION

The CDF experiment has made competitive measurements in $B_d^0$ mixing and rare $B$ decay searches; and also made one of the first attempts at a direct measurement

**TABLE 3.** Summary of rare $B$ decay searches.

| $B$ Decay Mode | Standard Model | CDF Run I | CDF II |
|---|---|---|---|
| $\mu^+\mu^-K^+$ | $(2-5)\times10^{-7}$ | $5.4\times10^{-6}$ | $2\times10^{-7}$ |
| $\mu^+\mu^-K^{*0}$ | $(1-2)\times10^{-6}$ | $4.1\times10^{-6}$ | $2\times10^{-7}$ |
| $B_d^0\to\mu^+\mu^-$ | $(0.6-2.4)\times10^{-10}$ | $6.8\times10^{-7}$ | $3\times10^{-8}$ |
| $B_s^0\to\mu^+\mu^-$ | $(2.5-4.5)\times10^{-9}$ | $2.0\times10^{-6}$ | $1\times10^{-7}$ |
| $B_s^0\to e^+\mu^-$ | forbidden | $6.1\times10^{-6}$ | $3\times10^{-7}$ |

of $\sin 2\beta$. This important work has shown that world-class $B$ physics can be done at a hadron collider and lays an important foundation for Run II.

The outlook for $B$ physics in the near future is very bright. Several experiments will produce measurements which will significantly constrain the CKM matrix and further our understanding of CKM physics and $CP$ violation. Both CDF and DØ will play an active roll in these $CP$ violation measurements, particularly in the decay $B^0/\overline{B^0}\to\psi K_s^0$.

The Tevatron program will also yield important measurements in the $B_s^0$ system with either a direct or indirect measure of $B_s^0$ mixing, as well as study of the $B_c$ system. These mesons will not be accessible at the $\Upsilon$(4s) $B$-factories.

Highlights of the $b$ physics program at the Tevatron in Run II will very likely include:

- an observation of $CP$ violation in the $B$ system
- direct or indirect measurement of $\Delta m_s$
- observation and study of the $B_c$ meson
- observation of "rare" $B$-decays
- stringent constraints on the CKM matrix and precision tests of the Standard Model.

In addition, if the past is any guide, additional methods and measurements will be developed as experience is gained with the upgraded detectors and larger data samples.

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