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PROSPECTS FOR MIXING AND CP VIOLATION AT THE TEVATRON

Michael Rijssenbeek
State University of New York at Stony Brook
Stony Brook, NY 11794-3800

The Fermilab $p\bar{p}$ Tevatron collider, operating at $\sqrt{s} = 1.8$ TeV, is a proficient source of B hadrons. The first collider run, Run I, has clearly proven that B states can be observed cleanly and can be studied in great detail in a hadron collider environment. In this presentation the future of the study of $B\bar{B}$ mixing and of CP violation at the Tevatron, with an upgraded machine and detectors, is discussed.

1 Introduction

The Tevatron Run I ended in May '96. The data, $\simeq 115\,\mathrm{pb}^{-1}$ per detector, led to the long-awaited discovery of the top quark with combined mass $175 \pm 6\,\mathrm{GeV}$, to the current precision measurement of the W mass with a combined uncertainty of 130 Mev, and to numerous new and improved measurements in electroweak physics, QCD physics, and searches for phenomena beyond the Minimal Standard Model (MSM).

In the field of B physics, CDF has presented a number of pioneering studies – e.g. $B \to J/\psi K_s^0$, Λ_b, B hadron cross section, lifetime and branching fraction measurements, measurement of mixing parameter x_d – that have solidly proven the feasibility of detailed B physics studies at hadron colliders [1]. The DØ Collaboration, with large muon coverage and excellent muon id, but without the benefits of a central magnetic field and of micro vertexing, has contributed with measurements of inclusive μ and b quark production cross sections, inclusive central and forward J/ψ production, and $B\bar{B}$ mixing [2].

2 The Tevatron Collider – Past and Future

At Fermilab the Main Injector ring, adjacent to the Tevatron ring, is under construction. The Main Injector is a conventional high intensity 150 GeV proton synchrotron, intended to improve the $\bar{p}$ production rate, and to increase the number of p's and $\bar{p}$'s available for collisions in the Tevatron. With improvements at the $\bar{p}$ production target, in the cooling and accumulator rings, and with 36 on 36 bunches in the Tevatron, the luminosity $\mathcal{L}$ will increase by a factor 5–10 in Run II (early 1999).

Under the name TeV33, further improvements are proposed: the addition of a permanent magnet antiproton storage and recycling ring. This would increase the luminosity by a factor five in the period before the LHC era.

The luminosity evolution for the various run periods is summarized in Table 1, with crossing interval and machine improvements [3].

Table 1: Typical luminosity, crossing interval, and machine improvements for the past and future Tevatron run periods.

Run Period	Typical $\mathcal{L}$	Bunch Interval	Improvements
1989	1.6×10^{30}	$3.0\,\mu$s	original design
Ia 1991–1993	5.4×10^{30}	$3.0\,\mu$s	Separators,
			$\bar{p}$ improvements
Ibc 1993–1996	1.9×10^{31}	$3.0\,\mu$s	Linac upgrade
IIa early 1999–	1×10^{32}	396 ns	Main Injector,
IIb	2×10^{32}	132 ns	$\bar{p}$ improvements
TeV33 2002– (?)	1×10^{33}	132 ns	Recycler ring,
			electron cooling

3 The Detector Upgrades

Both detector collaborations have ambitious upgrade plans (fully approved for DØ, partially approved for CDF as of June).

The CDF collaboration plans to extend its B-physics capability with a larger and improved 3-d, 5-layer silicon vertex detector (SVX II), an intermediate fiber tracker (IFT), an outer small-cell drift chamber (COT) with dE/dx, followed by a time-of-flight counter (TOF). Muon coverage will be increased (CMU, FMU), and the present plug calorimeter (PCAL) improved [5]. The flexible trigger system will use information on p_T, decay-length, dE/dx, and TOF, and will have a 40 kHz accept capability at the first (deadtime-less) level.

Extrapolations based on current performance predict that CDF will be able to address all CKM topics of interest with great precision and within a single experiment [5].

The DØ Collaboration is replacing its central and forward tracking systems completely. For Run II, a central/forward silicon barrels and disks micro-vertex tracker with $10\,\mu$m hit resolution will be installed, followed by 16 doublet-layers of scintillating fiber detection (axial and stereo views) with doublet $r\phi$ resolution of $130\,\mu$m. This tracking is surrounded by a 2 T, $1\,X_0$ superconducting solenoid, located inside the bore of the existing central cryostat of the liquid Argon-Uranium calorimeter. The resolution $\delta p_T/p_T$ is about 2% at

$p_T = 1\,\mathrm{GeV}$, and 4% at $p_T = 10\,\mathrm{GeV}$. After the solenoidal coil, and also in front of the end calorimeters, a preshower detector is placed to help in e/π separation and to sample the energy lost in the solenoid coil.

The calorimeter and muon system electronics are overhauled in order to cope with the reduced bunch interval. The muon system will be upgraded in areas of trigger, rejection of cosmics, and shielding. A p_T track trigger has been designed for level 1, and faster trigger processors will be installed.

DØ will concentrate on leptonic decay modes for its B physics program, making full use of its large $|\eta| \leq 2.5$ coverage for both μ and e triggers in combination with the fast p_T trigger at several thresholds. Because of cost, no impact parameter trigger is planned at the start of Run II.

4 $B\bar{B}$ Mixing and CP Violation at the Tevatron

The Tevatron is a high energy B factory: at $1.8\,\mathrm{TeV}$ the cross section for $b\bar{b}$ production is $\simeq 100\,\mu\mathrm{b}$, i.e. about 10^{11} b's are produced per fb^{-1} ($\simeq 1$ year), versus 10^7 for BaBar or Belle. Moreover, all B species are produced copiously: B_u, B_d, B_s, B_c, and b-baryons.

The increased luminosity and the shortened bunch interval require substantial upgrades to detectors, triggers, and DAQ. Although high p_T physics remains a priority of both collaborations, the availability of very large numbers of $b\bar{b}$ pairs has focussed strong interest onto the field of B-physics.

Both detectors plan to have acceptance with full momentum determination up to pseudorapidity $|\eta| \simeq 2-3$, i.e. a large fraction of the b-quark phase-space. Because many B decay modes of interest have small branching fractions, very selective triggers are required, with identification of one or more of the decay products. With the decay products being relatively soft, it is important to have low ($p_T \simeq 2\,\mathrm{GeV}$) trigger thresholds. At such thresholds the raw trigger rates are huge (up to $40\,\mathrm{kHz}$ for a central di-hadron trigger), and seriously challenge the trigger system and DAQ capabilities.

The study of $B\bar{B}$ mixing and CP violation aims to accurately determine elements of the CKM mixing matrix: their magnitudes and phases. Using both exclusive and semi-exclusive B decays, it is possible to over-constrain the CKM matrix, thereby testing the MSM. In the Wolfenstein approximation the CKM matrix elements are written in powers of λ, $\lambda \simeq V_{us} = \sin\theta_C$. Unitarity provides six non-trivial relationships between products of CKM elements. For the B system the most interesting relationship is:

$$\begin{aligned} 0 &= V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \\ &\simeq A\lambda^3\left[(\rho + i\eta) - 1 + (1 - \rho - i\eta)\right] \end{aligned} \tag{1}$$

These types of relationships in the SM are requirements of closure of "triangles" in the complex plane, where the sides are are the product terms in Eq. 1.

The CKM quantities of interest are measurable with various B decay channels, and generally rely on interference between two dominant amplitudes contributing to the decay mode, e.g. interference between $B^0 \to f$ and $B^0 \to \bar{B}^0 \to \bar{f}$ in cases where $f = \bar{f}$. In Table 2 a list of CKM parameters is given with the process that will (probably) measure it best. These, and many other processes have been investigated; beautiful and detailed overviews, both theoretical and experimental, can be found e.g. in the many contributions to the Snowmass '93 B Physics Workshop [4].

Table 2: Physics CKM quantities, "best" measurement mode, and measurement technique and critical detection issues.

Physics	Modes	Technique/Issues
β	CP asym. in $B \to J/\psi K_s$	μ trigger; low background
α	CP asym. in $B_d \to \pi\pi$	Di-hadron, decay-length trig.
		πX backgrounds, penguins?
γ	CP asym. in $B_s \to D_s K$	Trigger? Resolve oscillations?
		Fully reconstruct final states.
V_{td}/V_{ts}	B_d mixing, B_s mixing	Trigger? Resolve oscillations?
V_{ub}/V_{cb}	$B \to \rho\ell\nu,\ D^*\ell\nu$	Lepton trigger; rates?
QCD	B_c decays ($B_c \to J/\psi\pi$)	Lepton trigger; rates?
rare	$B \to \mu\mu, B^{\pm/0} \to \mu\mu K^{\pm}/K^*$	Lepton trigger; rates?

In the following we present an – incomplete – overview of the approaches by the collaborations for measurement of the CKM parameters.

sin(2β):

In the "golden" decay mode $B^0, \bar{B}^0 \to J/\psi K_s^0$, a CP eigenstate, the CP asymmetry A_{CP} is directly related to $\sin(2\beta)$: $A_{CP}(t) = \sin(2\beta)\sin(\Delta M_d t)$, where ΔM_d is the mass difference between the B mass eigenstates. The *measured* asymmetry is "diluted" by a factor D due to mis-tagging, and also due to mixing ($D_{mix} = x/(1+x^2) \simeq 0.47$) if the time-integrated asymmetry is measured.

The uncertainty δA_{CP}, depends on the number of events N, the B flavor tagging efficiency ϵ_{tag} and the "dilution" factor D from mis-tagging ($D \equiv (N_r - N_w)/(N_r + N_w)$, where $N_r (N_w)$ is the number of right(wrong) B tags) as follows: $\delta A_{CP}^2 = N \times \epsilon_{tag} D^2$. In Table 3 the product $\epsilon_{tag} D^2$ estimated for CDF is listed for several flavor tagging methods. The resulting uncertainty from CDF on $\sin(2\beta)$ expected in $1\,\mathrm{fb}^{-1}$ is between 0.14 and 0.08, competitive with results predicted for future B factories.

Table 3: Values of $\epsilon_{tag}D^2$ as measured in the present data, extrapolations based on predicted upgrade performance, and detection elements involved in the flavor tagging technique.

Tagging Technique	$\epsilon_{tag}D^2$ (measured)	$\epsilon_{tag}D^2$ (expected)	Upgrade
jet charge	1.3 ± 0.3	4.0	SVX II, IFT
central muon	0.7 ± 0.2	0.7	CMU
non-central muon	—	0.3	FMU, IFT
electron	—	1.0	PCAL, IFT
same-side π	1.5 ± 0.9	2.0	SVX II, IFT
total	3.5	8.0(?)	correlations?

DØ expects a $\sim 40\,\mathrm{MeV}$ resolution in the J/ψ-mass. Using a di-muon trigger, DØ expects a $\delta \sin(2\beta)$ of about 0.12 with $1\,\mathrm{fb}^{-1}$.

$\sin(2\alpha)$:

The decay mode $B_d \to \pi^+\pi^-$, a CP eigenstate, appears to be best for measurement of $\sin(2\alpha)$. The trigger requires di-hadrons of $p_T > 1.5\,\mathrm{GeV}$ plus a separated vertex. The method is similar to that above apart from two caveats. First, backgrounds from $B_s \to K\pi, KK$, and combinatorics will further dilute A_{CP}, and thus excellent mass resolution and π/K separation are essential. Second, the theoretical side of CP violation in $B_d \to \pi\pi$ is not clean, as spoiling contributions from penguin diagrams exist and are difficult to estimate.

In CDF the expected mass resolution is 20 MeV, whereas the COT plus TOF will provide π/K separation. With present theoretical estimates and assuming a very conservative signal-over-background ratio of 25%, CDF expects an uncertainty on $\sin(2\alpha) \simeq 0.10$ with this decay mode.

Angle γ:

The angle γ can be accessed with the decay modes $B_s(t) \to D_s^{\pm}K^{\mp}$ and $B^{\pm} \to DK^{\pm}$, with $D = D^0, \bar{D}^0, \mathrm{or} D^0_{CP+}$ the CP-even combination of D^0 and $\bar{D}^0$. Only all-hadronic decay modes can be used, e.g. $D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-$. In view of the large value of $x_s \geq 10$ ($x \equiv \Delta M/\Gamma$), the B_s decay modes have to be measured as function of proper time. The decays measure angle γ directly and are free from spoiling penguin contributions.

Alternatively the six decay modes $B^{\pm} \to DK^{\pm}$, $D = D^0, \bar{D}^0, \mathrm{or} D_{CP}$ maybe used. However, some of these branching fractions are very small. Also, these decays measure γ up to a hadronic phase from final state effects, which can be as large as 0.1 radians. Ideally, several processes and methods should be used to constrain and measure angle γ.

$|V_{td}/V_{ts}|$:

A measurement of this ratio, combined with the measurement of $|V_{ub}|$ and $|V_{cb}|$ from e.g. CLEO, yields an alternative measurement of the unitarity triangle, from its sides rather than from its angles. $|V_{td}/V_{ts}|$ can be derived from a measurement of $\Delta m_{B_s}/\Delta m_{B_d} = (B_{B_s} f_{B_s}^2)/(B_{B_d} f_{B_d}^2) \times |V_{ts}/V_{td}|^2$, where enters the ratio of theoretical form factors $(B_B f_B^2)$. Lattice QCD calculations presently determine the proportionality constant as 1.2 ± 0.1 and from LEP Δm_{B_d} is measured to $\pm 4\%$. ALEPH sets a lower limit on $\Delta m_{B_s} > 5.9\,\mathrm{ps}^{-1}$ (equivalent to $x_s > 9.5$) at 95% CL.

Thus oscillations will be rapid and the x_s reach will crucially depend on resolution in proper time, i.e. in decay length and B-momentum. For semi-leptonic decay modes, where the missing decay neutrino degrades the B momentum resolution, CDF expects to measure x_s up to 15, while fully reconstructed decays (e.g. $B_s \to D_s\pi$, $D_s 3\pi$, or $\psi\phi$) might reach to beyond 20. For the latter, Fig. 1 shows that with 3-D reconstruction of primary and decay vertices with the SVX, oscillations can be resolved well for $x_s = 20$.

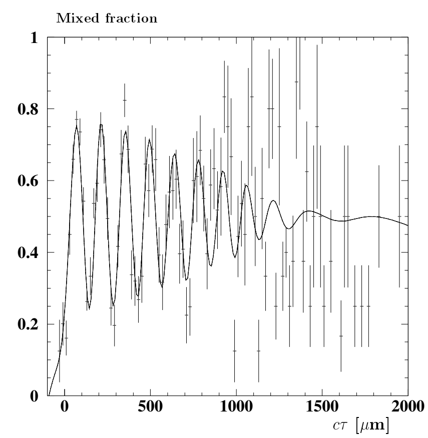

Figure 1: Simulation of the mixed B_s fraction for fully reconstructed B_s hadrons with the upgraded CDF detector in Run II

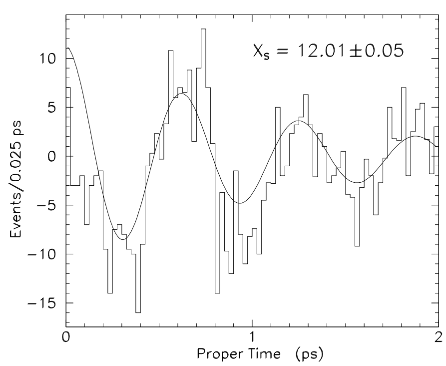

Figure 2: Simulation of difference between unmixed and mixed event samples of fully reconstructed $B_s \to D_s^\pm \pi^\mp(\pi^+\pi^-)$, $D_s \to \phi\pi(\pi\pi)$ for DØ in Run II

CP violation in fully "visible" hadronic modes $B_s \to D_s\pi(\pi\pi)$, $D_s^\pm \to \phi\pi(\pi\pi)$ decays is used to explore the capability of DØ to measure the mixing parameter x_s, with a simulation of the upgraded DØ detector. In Table 4 the estimated branching fractions and efficiencies for DØ are listed, indicating a yield of about 4000 fully reconstructed B_s in $1\,\mathrm{fb}^{-1}$. In the Fig. 2 the CP asymmetry is shown as function of proper decay time for $x_s = 12$. The oscillations are well resolved, and a reach up to 20 seems possible.

Table 4: Rates, Branching fractions, and efficiencies for fully reconstructed B_s for DØ

B-pairs per 1 fb^{-1}	4×10^{10}	
Fraction B_s	0.3 /pair	
BR($B_s \to D_s\pi(\pi\pi)$) (all charged second.)	0.03	(est.)
BR($D_s^\pm \to \phi\pi^\pm$, $\phi \to K^+K^-$)	0.018	(meas.)
BR($D_s^\pm \to \phi\pi^\pm\pi^+\pi^-$, $\phi \to K^+K^-$)	0.009	(meas.)
Tagging efficiency (e, μ)	0.3×0.22	(meas.)
Trigger efficiency $(p_T > 4)$	0.06	(meas.)
Geometry, vertex, & track efficiency	0.1	(simul.)

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