P238 Silicon Test Run at SPS-Collider and Perspectives for Hadron Collider B-Factories

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Introduction: The successful study of CP-Violation in B-decay will require large numbers of reconstructed exclusive B-Meson decays with good proper time, mass resolution and flavor tagged at production. How many events are needed? What is the best experimental method? In the context of proposals P238 to CERN, P845 to Fermilab and the 1990 Aachen LHC workshop (Erhan et al., CERN-PPE/91-10) extensive Monte Carlo simulation calculations on triggering, reconstruction and tagging have been performed to demonstrate that the large cross section, $\sigma(b\bar{b})$, at high energy hadron colliders can be efficiently exploited.

Far above threshold in hadron colliders, the production of B-Mesons from gluon-gluon fusion is forward-backward peaked, arising from the interaction of unequal energy partons. The efficient detection of such systems is therefore best done with open geometry forward collider detectors. Silicon microvertex detector planes perpendicular to the beam axis, similar to the geometry used in fixed-target experiments, will be installed inside the vacuum pipe close to the circulating beams and distributed throughout the source region. Data acquisition will be triggered by real-time calculations on the silicon data. A test silicon strip system with 6 planes and 43,000 channels has been successfully run at the Sp $\bar{p}$ S-Collider from September-December, 1990. Background free events are seen.

I summarize the Monte Carlo simulation calculations for the various efficiencies which determine the size of final data samples. The "CP-Reach" of the Beauty experiment proposed for the Fermilab Tevatron Collider (P845) is compared with a similar experiment at LHC and with the muon-triggered CDF experiment at the Tevatron and an e^+e^- B-Factory. P845 at the Tevatron is found to be comparable to or better than an e^+e^- experiment and much superior to a muon-triggered experiment. P845, with a mass resolution of 10 MeV, is also capable of excellent B_s -Mixing studies (not discussed in this report) and $\Delta M/T$ can be measured with an uncertainty of ± 0.1 for values as large as 15.

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The Open Geometry Forward Collider Detector: The device, shown in Fig. 1, has a maximum aperture of 600 mrad. Assuming both outgoing arms are instrumented, 55% (30%) of PYTHIA-generated $B \rightarrow J/\psi K_S \rightarrow \ell^+ \ell^- \pi^+ \pi^-$ events at the LHC (Tevatron) have all decay tracks contained in this aperture. The increase at higher energy arises from the fact that the 600 mrad aperture accepts the decay products of B-Mesons with momentum greater than about 20 GeV, which corresponds to increasingly smaller Feynman- x at higher energies.

A quadrupole magnet is used in Fig. 1 for the following reasons: (a) the absence of septum plate material near the beam minimizes interactions of outgoing particles; (b) particles with angles between 10 and 100 mrad receive minimal bending inside the beam pipe before they emerge and enter spectrometer 2; (c) the negligible stray field at the position of the silicon detectors does not distort the straight tracks, thereby minimizing the complexity of the online trigger calculation.

Silicon-Strip Microvertex Detector: The extended source size of the bunch crossing region and the need to minimize the extrapolation distance from measured track points in the silicon to an interaction vertex leads to a detector design in which the silicon planes, perpendicular to the beam line, are distributed along the intersection region with a spacing of 4 cm (16 or so planes would be used in a complete experiment).

For LHC R&D purposes, P238 was approved to test run at the Sp $\bar{p}$ S-Collider, a 6-plane 43,000 channel silicon strip microvertex detector (see Fig. 2) inside the vacuum pipe at 1.5 mm from the circulating beams. A 200 μ m thick aluminum window, which approximately followed the contours of the detectors, shielded the silicon detectors against RF pickup due to the passages of the beam bunches. Collapse of this window was avoided by establishing a secondary vacuum inside the Roman pots, in which the silicon detectors were found to function well.

Fig. 3 shows the top view of a typical event. Only pulse heights larger than $4\sigma_{\text{noise}}$ are shown. The negligible background of event-unrelated hits in the silicon show that a large silicon strip detector can be run in the manner proposed. A silicon strip length of 4.5 cm and the SVX-D chip result in a signal/background of 25/1. The real data are found to agree very well (not shown here) with Monte Carlo data generated using PYTHIA and a GEANT simulation of the detector. An article on the P238 silicon detector and the test results will be submitted to NIM in the near future.

Figure 1: Side View Of One Arm Of The Forward Beauty Detector. The silicon strip microvertex detector is at $z = 0$. The three spectrometers have apertures, 100-600, 10-100 and 2-10 mrad, respectively. The thin walled aluminum vacuum pipe which contains the circulating beams passes through the various detector components. There are three thin windows, one at $z \approx 0.3$ m, one at 4.8 m and one at 10 m. Conical sections with angles of 100 mr and 10 mr, respectively, connect the windows. The first magnet is a normal conducting quadrupole magnet with 2 m radius, 2m magnetic length and pole tip field of 1.2 Tesla. The second magnet is a superconducting dipole with $\int B dl = 5$ Tm and no septum plate. The third spectrometer contains a smaller superconducting dipole magnet with equal but opposite field integral and no septum plate (An identical spectrometer, or at least magnets with similar field integrals, are installed in the opposite arm for beam compensation).

Triggering Strategy & Monte Carlo Simulation: At the LHC, the ratio $\sigma(\text{inelastic})/\sigma(b\bar{b}) \approx 70$ mb/300 $\mu\text{b} = 230/1$ and defines the overall level of minimum bias suppression which is required. The overall strategy of the Level-1 trigger is to use the silicon digital information to search for events which are inconsistent with having a single vertex.

Complete GEANT simulations were made of the silicon detector response to PYTHIA-generated minimum bias, inclusive Beauty and Charm events. Following this, a Level-1 trigger algorithm was created and tuned to have the desired effects on these event samples. The algorithm provides a minimum bias suppression of 1/100 with a B-Meson efficiency of 30-50% (depending on final state

Figure 2: *Side and Front Views Of The P238 Silicon Detector Test System.* The planes are separated by 3.8 cm. Each contains eight 4.5 cm square single-sided detectors with four quadrants and independent x and y detectors separated by 2 mm. The pitch is currently 50 μm . The circulating beams pass between the independent upper and lower detector assemblies. The detectors are mounted on Roman pot assemblies, such that the upper and lower halves can be retracted to a safe position at 5 cm from the beams when there are beam manipulations. The detector assemblies can approach the beams as close as 1.5 mm or less for data taking.

multiplicity), corresponding to a beauty enhancement factor of 30 to 50. The algorithm is sufficiently concise to allow implementation in a pipelined (data-driven) trigger processor, with a computation time of about 15 μsec per event. The suppression of minimum bias background is sufficient to allow efficient transfer of accepted events to a "farm" of high performance parallel processors for further topology studies.

Monte Carlo Simulation of Reconstruction: Software was written to reconstruct Monte-Carlo Beauty events for specific final states, generated using PYTHIA. The underlying events are similar in structure to minimum bias events. Unit vectors describing track direction and position are obtained from the GEANT simulation of the silicon detector. Momentum measurement errors are simulated by randomly varying the generated momentum vectors, in accordance with expected spectrometer resolutions.

Events, whose B-meson decay products are completely contained in the spectrometer aperture, are passed through the trigger algorithm simulation software, and then through the reconstruction software in order to determine the reconstruction efficiency. Requiring a minimum B flight path of 0.5 mm allows the imposition of transverse momentum balance with respect to the B direction for each mass combination, thus greatly suppressing the combinatoric background under the B signal. Inclusive $b\bar{b}$, $c\bar{c}$ and minimum bias events were also passed through the same software chain for each exclusive final state in order to determine the combinatoric background levels, which are typically found to be about 10% or less from all sources. With a mean distance of 2 cm between an event primary vertex and the nearest silicon plane, the experimental resolution in the measured proper time, t , is found to be $\sigma(t)/t \approx 6\%$.

Monte Carlo Simulation of Flavor Tagging Efficiency: The large event loss which arises from requiring full reconstruction of the tag-providing system can be avoided by using as tags, only leptons

or charged kaons which are inconsistent with coming from the primary vertex. Tracks in the spectrometer, not associated with the reconstructed B, are examined and their silicon information used to ascertain that they do not emerge from the primary vertex. The time-integrated probabilities for oscillation and non-oscillation of their source B's are used to estimate the resulting mistagging.

A $K^\pm$ which contains the s-quark at the end of the $b \rightarrow c \rightarrow s$ chain uniquely identifies the flavor of its $\bar{B}$ -meson at decay. However, there are many sources of mis-tagging, such as kaons which are produced from the $s\bar{s}$ sea or from a $W^\pm$ in either the $b \rightarrow c$ or $c \rightarrow s$ transitions (which can have either sign). These are all accounted for, to some approximation, in the PYTHIA event generation and can be investigated by tabulating the supplementary kaons found in the spectrometer. For LHC events, 27% of the B-mesons in the spectrometer are found to have a tagging $K^\pm$ with impact parameter greater than 3σ from the primary vertex. The correct charge was found in 80% of these tags.

7% of LHC events with a B-Meson reconstructed in the spectrometer are found to also have a muon in the spectrometer from the accompanying $\bar{B}$. Requiring the muons to have $p_t > 1.2$ GeV (necessary to suppress those muons from other sources) and $p < 100$ GeV (to allow RICH identification) leaves 6.4% of the events with a tag quality (good tags/all tags) of 74%. Employing both lepton and charged kaon tagging, 40% of all reconstructed B-Mesons can be tagged with a tagging quality of about 78%.

CP-Violation Measurements and Dilution Effects: We have studied the sensitivity of the proposed apparatus to a measurement of a CP-Violation asymmetry in the decay to the "benchmark" CP-eigenstate $J/\psi K^0_s$. The time dependences of the decay of B_d and $\bar{B}_d$ into this final state are:

$$N(B_d \rightarrow J/\psi K_s) \approx A(t) \cdot e^{-t} \cdot [1 - \sin(2\beta) \cdot \sin(xt)] \quad (1)$$

$$\bar{N}(\bar{B}_d \rightarrow J/\psi K_s) \approx A(t) \cdot e^{-t} \cdot [1 + \sin(2\beta) \cdot \sin(xt)] \quad (2)$$

where t is the proper time measured from production in units of B mean life, τ ; β is an angle in the unitarity triangle and $x = \Delta M/\Gamma$ for B_d . $A(t)$ is the empirical acceptance function, which is found to have the form $A(t) = 4t^2/(1+4t^2)$ for accepted B events which pass the trigger simulation and reconstruction software. There is negligible distortion of the measured proper time distribution for times longer than about one mean life.

Ideally, each event would be perfectly flavor tagged at production and two clean samples of data would exist, described by Eqs. 1 and 2, respectively. In practice, of course, this is not the case and imperfect tagging moves events from one sample to the other and the measurement of $\sin(2\beta)$ is diluted. Thus, a sample of events, which appear to be the decay of a tagged B_d , actually consists of a superposition of true B_d described by Eq. 1 and true $\bar{B}_d$ described by Eq. 2, which were mislabeled because their tag-providing B_d oscillated to a $\bar{B}_d$ before decaying. Thus, the observed time distribution is a linear combination of Eq. 1 and Eq. 2, with weights approximately given by $(2+x^2)/[2(1+x^2)]$ and $x^2/[2(1+x^2)]$, respectively (These weights are the time-integrated probabilities for non-oscillation and oscillation of the tag-providing B, where x is its $\Delta M/\Gamma$).

Evaluation of this linear superposition shows that any measurement of $\sin(2\beta)$ invariably is multiplied by a dilution factor which, for our simple example of a single type of tag-providing B, is $1/(1+x^2)$. In practice, this is also multiplied by another factor, $(g-b)/(g+b)$, which accounts for good (g) and bad (b) tags, which may have the wrong sign because they come from extraneous sources. Finally, this dilution factor is averaged over all three types of tag-providing B-Mesons. We estimate an overall dilution factor, $D = 0.45$. In a real experiment, D can be obtained by measuring the amplitude of B_d oscillations to a large branching ratio non-CP-eigenstate.

In order to determine the required sample size for any desired error in a measurement of $\sin(2\beta)$, Monte Carlo event samples were generated according to Eqs. 1 and 2, assuming various values of $\sin(2\beta)$ and D . Simultaneous Maximum Likelihood fits of Eqs. 1 and 2 were then made to the observed time distributions. The resulting error in $\sin(2\beta)$ is found to depend on sample size, N (B plus $\bar{B}$ events) in the following way:

$$\delta[D \cdot \sin(2\beta)] = 1 / \sqrt{(0.56N)} \quad (3)$$

where the constant 0.56 is a statistical factor which is characteristic of the time dependent fit and our particular acceptance function. In the following section, we define $D'^2 \equiv 0.56 \cdot D^2$, such that $\delta[\sin(2\beta)] = 1 / \sqrt{(D'^2 N)}$.

Comparison of Different Experimental Possibilities: Table 1 summarizes the parameters which determine the event yield for our benchmark state. The values are compared for four experimental situations, an e^+e^- B-Factor, the type of silicon-triggered open geometry forward detector discussed here at both the Tevatron Collider and the LHC, and the muon-triggered central detector CDF at the Tevatron. We see that the optimized Tevatron P845 experiment and an e^+e^- B-Factor have comparable CP-Reach, while a muon-triggered and tagged central experiment such as CDF lags far behind. The ultimate measurements of CP-Violation will likely be done at the LHC and SSC.

Table 1: Comparative "CP-Reach" for $B_d^0 \rightarrow J/\psi K_s^0$

	LHC (SSC) ^{c)}	P845 Tevatron	CDF ^{b)} Tevatron	SLAC e^+e^-
Peak Luminosity	10^{31}	10^{31}	10^{31}	3×10^{33}
$\sigma(b\bar{b})$	300×10^{-30}	50×10^{-30}	50×10^{-30}	1.2×10^{-33}
2-Arm Geom. Accept.	.55	.30	1	1.0
Trigger Efficiency	.30	.30	.0083	1.0
Reconstruction Eff.	.25	.32	1	.58
Tagging Efficiency	.40	.32	.04	.45
D'^2 (see text)	$.56(.45)^2$	$.56(.45)^2$	$.56(.45)^2$	$(.58)^2(.86)^2$
Rate ^{a)} : $D'^2 N$ (Hz)	2700×10^{-7}	250×10^{-7}	4.5×10^{-7}	140×10^{-7}
$\delta(\sin 2\beta)$, $t = 2 \cdot 10^7$ s	0.014	0.045	0.33	0.060

a) $D'^2 N$ is calculated as the product of all previous quantities in the table and the factors $[2 \cdot BR \cdot (0.4)]$, where "2" counts both B and $\bar{B}$, $BR = 6 \cdot 10^{-5}$ is the branching ratio to the observed $\ell^+ \ell^- \pi^+ \pi^-$ final states and 0.4 is the hadronization probability to B_d (0.5 is used for e^+e^-). D' is assumed to be the same for all hadron collider experiments.

b) The CDF numbers correspond to an observed cross section of 10 pbarn (muons only) expected during the forthcoming 1992-1993 run (Paul Tipton, private communication).

c) Rate for SSC will be somewhat larger due to increases in $\sigma(b\bar{b})$ and acceptance.