Prospects for Beauty Physics
at Hadron Colliders

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INTRODUCTION

Nature wants us to do B physics!

- The B lifetime is ~ 1.2 psec $\Longrightarrow$ can observe the decay vertex separated from the production vertex. The B's can be isolated even when produced in hadronic interactions.
- $B^0 - \bar{B}^0$ mixing is large $\Longrightarrow$ phenomenology rich in quantum-mechanical effects.
- The cross-sections for $gg \to B\bar{B}$ are large at collider energies.[1,2]

Collider	$\sqrt{s}$ (GeV)	$\sigma_{B\bar{B}}$ (μb)	$\sigma_{B\bar{B}}/\sigma_{\text{tot}}$
RHIC	0.5	10	1/4000
TEV I	2	40	1/1000
SSC	20	500	1/200

- The signal to noise for beauty at the SSC is comparable to that for charm in fixed-target photoproduction.
- B-decay products are **soft**: 90% of all tracks have $P_T < 5$ GeV/c.
- Can follow a classic prescription for detailed study of particles: measure the decays to few-body, all-charged final states.
- CP violation is accessible.
    - A 3-σ signal for a CP-violating asymmetry of 0.1 requires 1000 reconstructed events.
    $\Longrightarrow$ need 10^8 reconstructible pairs if branching fraction $= 10^{-5}$.
    $\Longrightarrow$ need 10^{10} pairs produced if reconstruction efficiency $= 1\%$.
    - The luminosity needed to produce such a sample in 10^7 sec is then
    $\mathcal{L} = 10^{32}$ cm^{-2}sec^{-1} at RHIC
    $\mathcal{L} = 2.5 \times 10^{31}$ cm^{-2}sec^{-1} at TEV I
    $\mathcal{L} = 2 \times 10^{30}$ cm^{-2}sec^{-1} at SSC
- The crispness of the CP-violation physics encourages us to tackle difficult issues.
    - How to survive in **high multiplicity.**
    100 tracks/event; 100 samples/track $\Longrightarrow \sim 10^4$ words/event.
    Can readily find patterns if detector occupancy is $\sim 10^{-3}$.
    $\Longrightarrow$ need $\sim 10^7$ detector elements ($\sim 10^5$/layer).
    - How to survive at **high rate.**

Have 5–10 MHz event rate at $\mathcal{L} = 10^{32}$ cm^{-2}sec^{-1}.

Need sparse readout and buffering of the 10^4 elements struck per event.

$\longrightarrow$ 50–100 Gword/sec raw event rate!

Front-end analog triggers reduce event rate to <100 kHz.

Numeric-processor farm reduces rate to 1–2 kHz.

Archival data rate ~100 Mbyte/sec to video tapes.

- The same detector concept applies to RHIC, TEV I, and the SSC. FIGURE 1 shows the Beauty spectrometer as conceived at the 1988 Snowmass Workshop.

PREJUDICES ABOUT CP VIOLATION IN THE B-$\bar{B}$ SYSTEM

- The best signal for CP violation is an asymmetry:

$$A = \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})}.$$

- The theoretical interpretation of A is clean only when $f = \bar{f} = CP$ eigenstate.

  $\Longrightarrow$ must tag the other B of the B-$\bar{B}$ pair.

  $\Longrightarrow$ 'self-tagging' modes like $B^0 \rightarrow K^-\pi^-$ or $D^+\pi^-$ might be more accessible experimentally, but are less useful theoretically. (Like ϵ'/ϵ in $K^0 \rightarrow \pi\pi$ these depend on penguin diagrams . . .)

- Large $A \longleftrightarrow$ small Γ, in most models.

- To reach S standard deviations in a measurement of A for mode $B \rightarrow f$ with branch Γ, need N produced B's, where

$$N \approx \frac{S^2}{\Gamma A^2}.$$

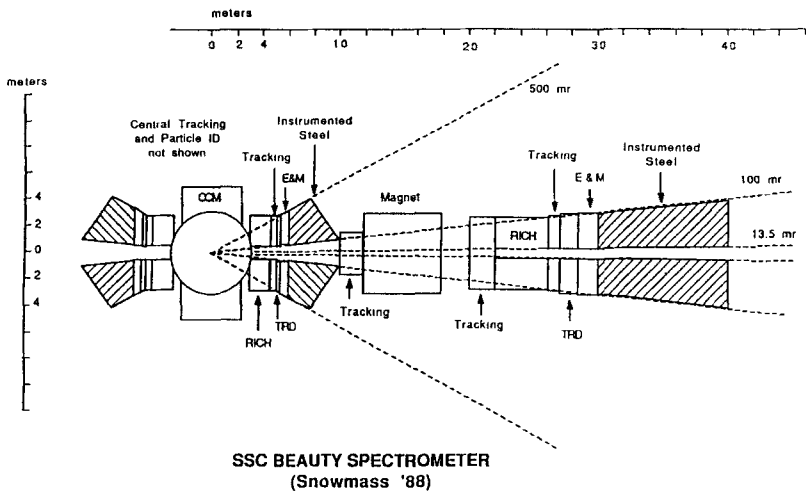Example: $S = 3, A = 0.1, \Gamma = 10^{-5} \Longrightarrow N = 9 \times 10^7$.

SSC BEAUTY SPECTROMETER
(Snowmass '88)

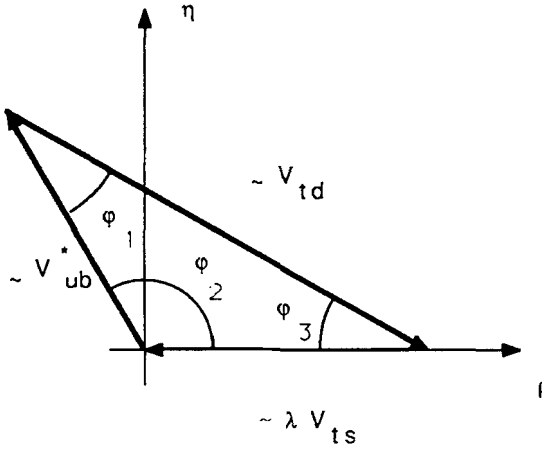FIGURE 1. A beauty spectrometer concept.

FIGURE 2. The unitarity triangle.

- CP violation and the KM matrix (Wolfenstein):

$$V_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \mu\lambda^3(\rho - i\eta) \\ -\lambda & 1 & \mu\lambda^2 \\ \mu\lambda^3(1 - \rho - i\eta) & -\mu\lambda^2 & 1 \end{pmatrix}.$$

$\lambda \sim$ the Cabibbo angle.

μ is known via the B lifetime.

$\eta \neq 0 \leftrightarrow CP$ violation.

But, ρ, η are not well determined from the $K\overline{K}$ system.

  - The B-$\overline{B}$ system is the place!

- Bjorken's trick: unitarity of $V_{KM} \Rightarrow V_{td} + \lambda V_{ts} + V_{ub}^* \approx 0$.

  $\Rightarrow$ these 3 vectors form a closed triangle. On dividing the lengths by $\mu\lambda^3$, we obtain FIGURE 2.

  Since the base is known, the experimental challenge is equivalent to measuring the 3 interior angles ϕ_1, ϕ_2, ϕ_3.

- For $B \rightarrow f$ with f a CP eigenstate, the asymmetry A depends only on $\sin\phi$

  $A \sim \sin 2\phi_1$ for $B \rightarrow \psi K_S, D\overline{D}K_S, \psi\pi\pi, D\overline{D}, D^0\pi^+\pi^-, \ldots$

  $A \sim \sin 2\phi_2$ for $B \rightarrow \pi^+\pi^-, p\overline{p}, \ldots$

  $A \sim \sin(\phi_2 - \phi_1)$ for $B \rightarrow \overline{D}^{*0} K_S, \ldots$

- An overconstrained study of CP violation in the KM matrix requires the observation of many decay modes.

  $\Rightarrow$ need a general purpose detector with particle identification.

  $\Rightarrow$ need tagging of the second B.

  $\Rightarrow$ an extensive program for the 1990's!

PRE-CP PHYSICS IN THE B-$\overline{B}$ SYSTEM

- $\sigma_{B\overline{B}} \leftrightarrow$ gluon structure functions at collider energies.
- B_d-$\overline{B}_d$ and B_s-$\overline{B}_s$ mixing. The latter is large but surprisingly hard to measure owing to rapid oscillations.

- $\Gamma(B \rightarrow f)$ for likely CP-violating modes
  $\Rightarrow$ a rich program even before CP violation.

RECENT DETECTOR PROPOSALS

1. March 1987, Letter of Intent to FNAL by Volk, Reay et al.[3]
2. March 1987, Letter of Intent to FNAL by Van Berg, Lockyer et al.[4]
3. July 1987, SSC Beauty Spectrometer at the Berkeley Workshop.[5]
4. November 1987, Dipole Beauty Spectrometer at the FNAL Beauty Workshop.[6]
5. June 1988, Status Report of the Fermilab B Collider Study Group.[7]
6. July 1988, SSC Beauty Spectrometer at the Snowmass Workshop.[8]
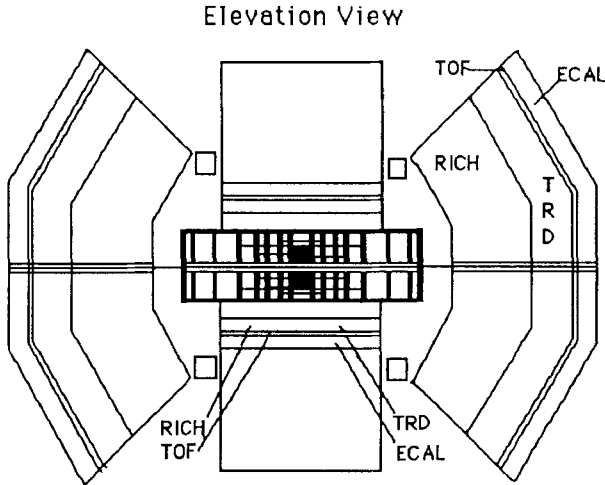
Elevation View

FIGURE 3. Overview of the BCD detector.

7. July 1988, Solenoid Beauty Spectrometer at the RHIC Workshop.[9]
8. August 1988, Letter of Intent to CERN by Brandt, Schlein et al.[10]
9. October 1988, Letter of Intent for a Bottom Collider Detector for the Fermilab Tevatron.[11]

OVERVIEW OF THE BOTTOM COLLIDER DETECTOR

We will use the recently proposed Bottom Collider Detector[11] as an example. A schematic side view is shown in FIGURE 3. The design is driven by the need for large angular acceptance, good momentum resolution for low-momentum tracks, precision vertexing, and particle identification. Calorimetry is not important except for electron

identification. The basic character of the detector is 'central,' but with greater emphasis on the angular region $2° < \theta < 30°$ than in present detectors designed for W and Z physics.

• A dipole magnet is chosen to optimize the detection of tracks produced between $2° < \theta < 178°$ (pseudorapidity: $-4 < \eta < 4$). The kinematics of B-$\bar{B}$ production are such that both forward and central tracks must be measured well to have a high geometric acceptance, while transverse momenta greater than 5 GeV/c are seldom of interest. A dipole magnetic field oriented perpendicular to the beams is the best and simplest solution. A low-field (1 Tesla), large-diameter magnet is preferable for pattern recognition of low-momentum tracks.

• The magnet design calls for circular pole tips of 4-m diameter, separated by a 4-m gap. This large gap permits a tracking system with 75–100 samples per track, the minimum acceptable number in a high-multiplicity event, while still accommodating the EM calorimeter, TRD, and RICH counters inside the gap.

• The vertex detector is designed to find the secondary vertices of B particles with high accuracy and efficiency, thereby isolating the B from the rest of the event. The resulting ability to study the time evolution of the states is particularly advantageous for CP studies. Extensive Monte Carlo simulation indicate that 3-d vertex reconstruction is necessary to achieve good pattern recognition, and that the system should have a worst-case impact-parameter resolution of <20 μm. All tracks should intersect at least 3 planes with an angle of incidence <45°. These requirements, along with the length of the interaction region, led to a hybrid design of barrels and planes of double-sided silicon detectors. These devices are located outside the beam pipe, beginning at 1.5-cm radius, to minimize the effects of multiple scattering. Monte Carlo studies of this design, where tracking efficiencies were 100%, gave an efficiency of finding B vertices of ~45%. A preliminary mechanical model of this detector design has been constructed.

• The vertex detector relies on the gas tracking system for most of the pattern recognition. The tracking system is designed for efficient and rapid 3-d pattern recognition of tracks over the full angular range. There are 75–100 samples along each track. The technology used is thin-walled straw tubes, pressurized to 3 atmospheres and arranged in superlayers. Such straw tubes permit a measurement error of 40 μm per hit. This high precision will allow a mass resolution of 20 MeV/c² and an extrapolation error into the silicon vertex detector of 50 μm. Good mass resolution is desirable to separate B_d from B_s, and to set a narrow mass window around the B as a rejection against combinatoric background.

• Particle identification is important in reducing the combinatoric background, especially for modes such as $B \rightarrow K\pi$ and $B \rightarrow p\bar{p}$. Electron identification is required for triggering and tagging the particle-antiparticle nature of the B. The design incorporates TRD's RICH counters, and an electromagnetic calorimeter over the full detector acceptance and for the full momentum range of the B-decay products.

• The trigger and data-acquisition system is designed to handle a luminosity of 10^{32} cm^{-2}sec^{-1} and data-flow rates of GigaBytes per second. The trigger philosophy is to assemble the full event as soon as possible and pass it to a farm of numeric processors where a variety of trigger algorithms can be implemented in software. The system is based on the latest communications-industry technology, which represents a new approach for high-energy physics experiments and is suitable for SSC data rates.

• An initial cost estimate for the detector is $30M.

In the space remaining we elaborate slightly on two issues, a possible 'topology trigger,' and the data-acquisition system based around a 'barrel switch.'

TOPOLOGY TRIGGER

A first-level trigger is desired that might be straightforward to implement while reducing the event rate by 20–50. The 'topology trigger' simply counts the number of
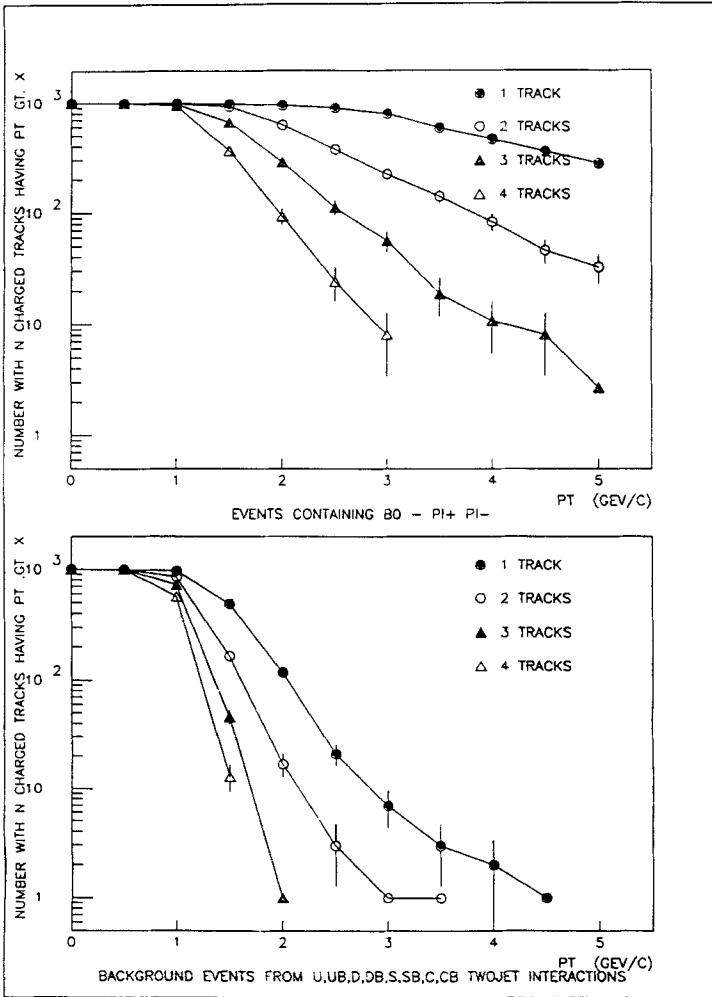

FIGURE 4. (*upper*) The number of charged tracks above a given P_T for events containing a $B \rightarrow \pi^+\pi^-$ decay, according to an ISAJET simulation; (*lower*) the same for events without any B's.

charged tracks in the event above a given cut in P_T. This is illustrated in FIGURE 4, based on an ISAJET simulation.

If a cut on only a single track could be made reliably, we see that a cut at $P_T = 2.5$ GeV/c would yield a factor of 50 reduction in the event rate at the expense of only a 10% loss of events with a 2-body decay such as $B \rightarrow \pi^+\pi^-$. Or, if two tracks are each required to be above 2 GeV/c, the desired reduction of the total event rate could be achieved with 40% loss of 2-body B decays. The efficiency for many-particle B decay is, of course, less.

DATA ACQUISITION

The architecture of the data-acquisition system takes advantage of several new approaches; in particular:

- Digital transmission over fiber-optic cables.
- A simple 'barrel shifter' switch for event building at 100 kHz.
- A farm of ~2000 numeric processors, especially suited to tracking problems, which implement the second-level triggers, employing full reconstruction algorithms for some detector systems.

A block diagram of the proposed data-acquisition system is shown in FIGURE 5. The data flow is from top to bottom. Prompt triggers (such as the topology trigger) will first reduce the data rate by a factor of 20–50, using a subset of the detector elements labeled A–Z in FIGURE 5. From this point on there is no other specially built logic for triggering. If the event is accepted by the first-level trigger, the data fragments are transmitted over fiber-optic cable to the Event-Builder Switch. There can be any number of data sources from each detector system.

The Event-Builder Switch is based on the high-speed technology of a telephone exchange. The 'barrel-switch' technique can accept parallel inputs from a large number of sources and reorganize these into a set of output streams, each stream containing only information from a single event. Data rates of tens to a few hundreds of GigaBytes/sec are possible.

The Receiver/Formatters format the data into structures suitable for high-level language programs, and then pass the events into one member of the large farm of numeric processors. Each of these processors will be the equivalent of about 40 VAX 780's and will implement the second-level trigger in software. They should reduce the event rate by another factor of 100, leaving a rate of ~1 kHz at a luminosity of 10^{32} cm^{-2}sec^{-1}, which can be archived to tape on video cassettes.

SUMMARY

The cross-section for $gg \rightarrow B\bar{B}$ is relatively high at collider energies, so that a one-year run at RHIC or TEV I might yield $>10^{10}$ B-$\bar{B}$ pairs, and $>10^{12}$ pairs at the SSC. The challenge to the experimenter is to trigger on and reconstruct a significant fraction of this sample. Detectors are being proposed that make extensive use of silicon vertexing, VLSI readout, and massive online numerical processing with the goal of
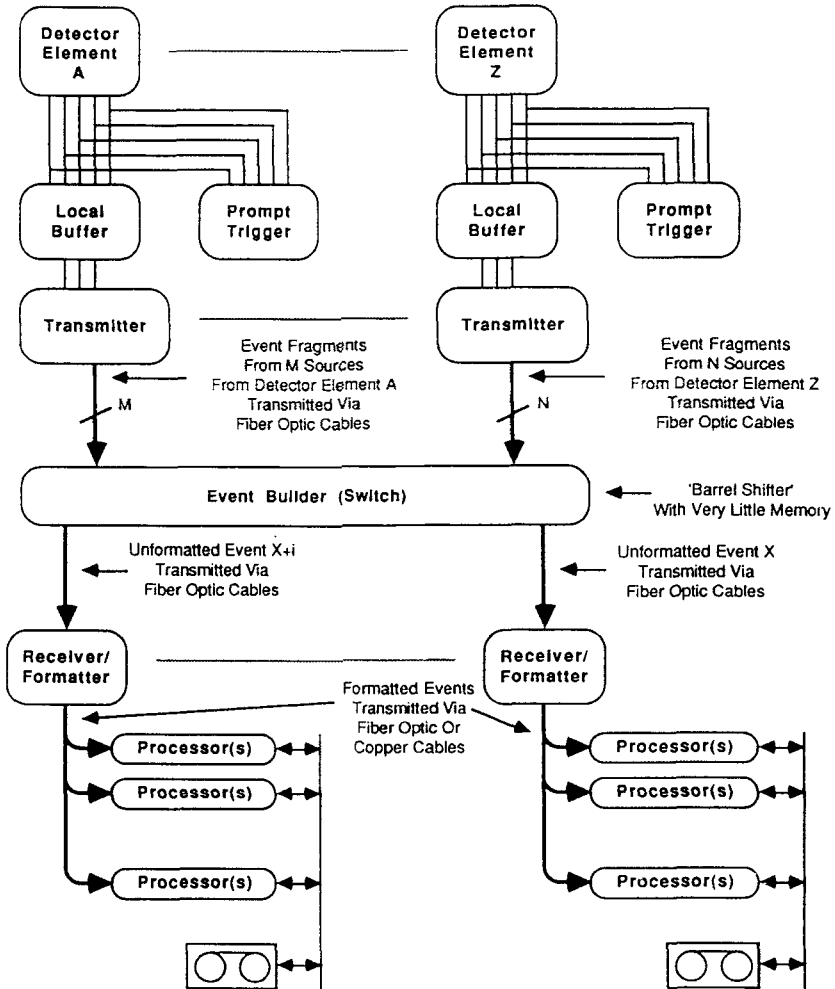
FIGURE 5. Block diagram of the proposed data-acquisition system.

maintaining a 1% efficiency for few-body decays to all-charged final states. If achieved at the SSC for $\mathcal{L} = 10^{32}$ cm^{-2}sec^{-1}, this would be equivalent to an e^+e^- B factory operating at $\mathcal{L} = 10^{36}$ cm^{-2}sec^{-1} and 100% reconstruction efficiency. Even at RHIC or TEV I with 10^8 reconstructible B's, the strongest signals for CP violation in the B-$\bar{B}$ system would be accessible.

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