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Prospects for Heavy Flavor Physics at Hadron Colliders

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The role of hadron colliders in the observation and study of CP violation in B decays is discussed. We show that hadron collider experiments can play a significant role in the early studies of these phenomena and will play an increasingly dominant role as the effort turns towards difficult to measure decays, especially those of the B_s meson, and sensitive searches for rare decays and subtle deviations from Standard Model predictions. We conclude with a discussion of the relative merits of hadron collider detectors with 'forward' vs 'central' rapidity coverage.

Introduction

We are approaching the exciting time in particle physics when experiments **will** achieve the sensitivity needed to study CP violation in B decays. My task in this paper is to describe the role that hadron colliders will play in this enterprise. The main points that I will try to make are:

- The next round of experiments will almost certainly establish significant evidence for CP violation in the B-system;
- The two Tevatron Collider experiments, CDF and D0, have an excellent opportunity to play an important part in this first round;
- For a variety of reasons, having to do with the limited statistics that will be available from the first round of experiments and with the growing understanding of the theoretical difficulties in interpreting the results, this round of experiments will open up the study of CP violation in B decays but is unlikely to close it out; and
- Hadron collider B experiments will play an even larger role in the second round of 'precision' CP studies because of the large number of b-hadrons they produce. Experiments with forward rapidity coverage, rather than central rapidity coverage, may have the best chance of achieving the high efficiency required for this phase. Experiments in the forward direction, such as the BTeV experiment being developed at Fermilab, also have the ability to study charm in hopes of finding physics beyond the Standard Model.

The plan of the paper is as follows: in section 1 we review briefly the physics of CP violation, list the decays that need to be measured, and discuss the accuracy that is required; in section 2, we discuss the sensitivity that will be achieved on some of these measurements at e^+e^- colliders running at the $\Upsilon(4S)$; in section 3, we discuss the sensitivity achievable by CDF and D0 when they resume taking data at the Fermilab Tevatron Collider in the year 2000; and in the last section, we consider the options for pushing these studies to higher sensitivity than will be achieved in this first round of experiments. We review the argument that detectors with forward rather than central rapidity coverage will give the best results on the widest variety of important decays modes at the hadron colliders and describe one such experiment, BTeV, which is being proposed for the Tevatron.

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1. Program of Measurements of B Decays Required to Explore the CKM Matrix

1.1. Brief Introduction to the Standard Model Mechanism for CP Violation

The weak interaction does not obey the flavor symmetry which is a characteristic of the strong interaction. It has the ability to transform quarks of one flavor into another. This 'quark mixing' is expressed by the Cabibbo-Kobayashi-Maskawa(CKM) matrix[1], which can be viewed as giving the mixing of the 'flavor' eigenstates of the charged 1/3 quarks into the 'mass' eigenstates of the weak interaction. The charge 1/3 weak eigenstates then couple to the charge 2/3 quarks via Fermi-like weak interaction. The CKM matrix is unitary and, for three generations of quarks, can be shown to have four independent parameters – three real ones and a complex phase. The CKM Matrix, V, is shown here in the Wolfenstein representation[2], to order λ^3 ($\lambda = 0.22$, the sine of the usual Cabibbo angle):

$$\left(\begin{array}{ccc|c} d & s & b & \\ \hline 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) & u \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 & c \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 & t \end{array}\right)$$

The $V_{q_{2/3}q_{1/3}}$ element can be read by following the quark labels at the side and top of the matrix.

CP violation produces a difference in the rates of the decays of a particle into some final state and its antiparticle into the CP conjugate state. This kind of asymmetry is due to interference effects. It is the non-zero value of η (or equivalently, the complex phase) which is responsible for CP violation in the Standard Model. In order to have a non-zero asymmetry, in addition to a weak phase (non-zero value of η), we must have the following conditions:

- there must be at least two processes (preferably with approximately equal amplitudes) that contribute to the overall decay amplitude A; and
- A must have a SECOND phase, besides the CKM phase, that does not change its sign under a CP transformation so that destructive interference can take place in one process and constructive interference can take place in the CP-transformed process, thus giving the asymmetry. This phase can be a strong interaction phase shift or the time-dependent phase introduced by mixing.

Other explanations of CP violation invoke new interactions and fields which are outside the Standard Model. Small CP-violating effects have been observed in the neutral kaon system[3] and, while they can be explained by the Standard Model mechanism, one can not yet rule out other explanations.

There are three basic interference mechanisms for generating CP asymmetries[4]. They are:

- Indirect CP violation: This is due to the interference between the different 'box' diagrams responsible for mixing in the neutral mesons, $B^o(\bar{B}^o)$ and $B^o_s(\bar{B}^o_s)$. This interference effect is the one believed responsible for the OBSERVED CP violation in the neutral kaon system. In the context of the Standard Model, this kind of CP violation is predicted to be small for B mesons.
- Direct CP violation: This is due to the interference when a weak decay can occur through two diagrams, one of which involves the weak phase. The phase difference which does not change sign under CP conjugation is provided by phase shifts caused by strong final state interactions. Predictions of the magnitude of this kind of CP violation depends on theoretical estimates of strong phase differences created by final state interactions and are very uncertain. The asymmetries could be at the few percent level. While observation of these effects would be highly significant, there is no easy way to extract the value of the CKM phase from them because it always appears tangled up with a strong phase shift.

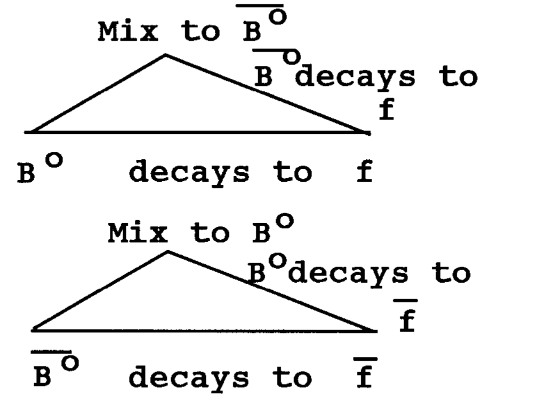

Figure 1. Interference effect between a direct decay and a mixing process followed by a decay to the same final state.

- 'Mixing-induced' CP violation: This involves the interplay between decays and mixing. It occurs for neutral mesons (only) when the neutral meson can decay into both a state f and its charge conjugate state $\bar{f}$. This kind of CP violation is shown in Fig. 1. The Standard Model predicts large mixing-induced CP asymmetries in B-decays. Moreover, the second 'phase' that is required to produce CP violation is the phase due to mixing. This phase is can be measured directly once mixing is observed and is now known to high accuracy for the B^o. It is therefore easy to extract the weak phase without ambiguity. The situation is more complicated for the B^o_s where the mixing is so rapid that it has not yet been measured accurately and only a lower limit to the mixing parameter exists.

The CKM matrix provides important clues concerning which decays will exhibit large CP asymmetries. The unitarity requirement gives us various equations which can be represented graphically in the complex ρ-η plane. The size of various CP violation asymmetries can be shown to be proportional to the sines of twice the angles of these triangles and the angles can be related to specific measurable decay asymmetries. One such equation and the corresponding triangle has all three sides roughly equal and it is therefore guaranteed that the angles will all be large. The relation is

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \qquad (1)$$

It is conventional to divide this equation by the length of the side $V_{cd}Vcb^*$ (which is real in the Wolfenstein parametrization), and to use the SM prediction that

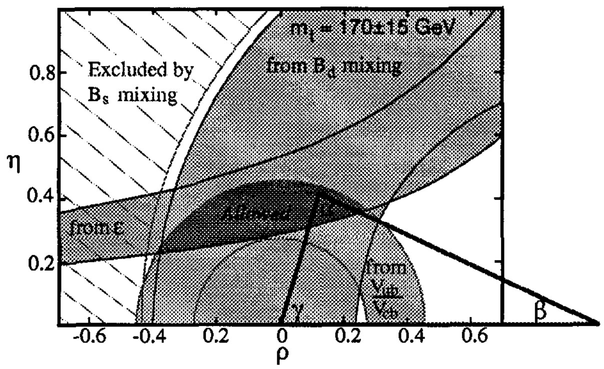

Figure 2. Unitarity triangle showing existing constraints on ρ and η.

V_{tb}, V_{ud} are very close to 1, giving

$$\frac{V_{ub}}{|\lambda V_{cb}|} + \frac{V_{td}}{|\lambda V_{cb}|} + 1 = 0 \quad (2)$$

This triangle is shown graphically in Fig. 2[5]. Much is already known about the shape of this triangle since the length of the sides can be related to decays that have already been measured. For example, $B^o\bar{B}^o$-mixing gives the length of the side of the triangle that involves V_{td}. The rate of charmless semileptonic decay is simlarly proportional to $|V_{ub}|^2$ and gives another side of the triangle. If one accepts the Standard Model explanation of CP violation in K^o decay, then the measured value of the parameter ϵ gives a curve in the ρ-η plane. The constraints on the value of ρ and η, the parameters of the vertex of the CKM triangle, are also shown in Fig. 2.

This unitarity triangle suggests that large asymmetries will occur in decays that involve V_{td} and V_{cb}. Since V_{td} appears in the box diagram responsible for B^o-mixing, this suggests a mixing-induced process involving a $b \rightarrow c$ transition. One such decay, which has a very nice experimental signature is the decay $B^o \rightarrow \psi K_s$. Moreover, if one observes the decay mode through the $\psi \rightarrow \mu^+\mu^-$ or e^+e^- and the $K_s \rightarrow \pi^+\pi^-$, the final state is itself a CP eigenstate. Refering to Fig. 1, $f = \bar{f}$. This produces many simplifications. The asymmetry from this mixing-induced decay is given by the equations:

$$\begin{aligned} G &= |A(f)|^2 e^{-\tau} [1 + \mathrm{ACPV}\ \sin(x_q \tau)] \quad (3) \\ \bar{G} &= |A(f)|^2 e^{-\tau} [1 - \mathrm{ACPV}\ \sin(x_q \tau)] \end{aligned}$$

where, in this case, G represents the decay rate for $B^o \rightarrow \psi K_s$ and $\bar{G}$ is the charge conjugate. Observation of these time distributions would be a convincing demonstration of CP violation. If the oscillation is not too rapid, as is the case for the B^o, there will also be a large time-integrated asymmetry. If the oscillation is rapid, as it is for the B_s, the oscillations wipe out the integrated asymmetry and a study of the full time-dependence is necessary. Finally, each event must be labelled according to its 'initial' flavor to decide which distribution to enter it in. This is called 'tagging' and is discussed below.

Similarly, the angle α can be seen to be related to V_{td} and V_{ub}. It can be explored in a 'mixing-induced' decay of B^o involving V_{ub}. The most promising decay of this kind appears to be $B^o \rightarrow \pi^+\pi^-$.

For ψK_s, $A(f)$ in equations 3 and 4 will be proportional to $V_{cb}^* V_{cs}$ and ACPV turns out to be equal to $\sin 2\beta$; and for $\pi^+\pi^-$ it will be proportional to $V_{ub}^* V_{ud}$ and ACPV is equal to $\sin 2\alpha$. Note that V_{td} and V_{ub} contain the imaginary part $i\eta$. The values of $\sin 2\beta$ and $\sin 2\alpha$ are related to ρ and η as follows:

$$\begin{aligned} \sin 2\beta &= \frac{2\eta(1-\rho)}{(\eta^2 + (1-\rho)^2)} \quad (4) \\ \sin 2\alpha &= \frac{2\eta(\rho - \eta^2 - \rho^2)}{(\eta^2 + \rho^2)(\eta^2 + (1-\rho)^2)} \end{aligned}$$

In the Standard Model with its three generations, unitarity requires these triangle relations. Thus, $\alpha + \beta + \gamma$ must really add up to 180^o. Some extensions to the Standard Model do not result in such relations so deviations from them could be a signal for new physics. It is highly desirable to have statistically accurate measurements of all three angles and all three sides. Unfortunately, although many ideas have been proposed, there seems to be no method for measuring the angle γ which is 'easy' to do experimentally and is free of theoretical ambiguities. Moreover, even the extraction of α from the decay $B^o \rightarrow \pi^+\pi^-$ has both experimental and theoretical difficulties. On the theoretical front, there is a Penguin diagram that can also contribute to the decay rate and that depends on the weak phase and possibly a strong phase. If the Penguin amplitude is large, as recent results discussed below suggest, the interpretation of this decay gets very complicated. It also appears that the branching fraction to $\pi^+\pi^-$ may be lower than expected so that it will be difficult to get a statistically precise measurement from this mode.

The Standard Model predicts a wide variety of CP asymmetries, some quite large, in decays of hadrons containing b-quarks. It is important to carry out a systematic investigation of Standard Model predictions for CP violation in B decays to see to what extent the Standard Model provides a consistent picture and to look for departures from that picture which could be due to new physics which is outside the Standard Model.

The Standard Model also predicts very small CP violation effects in charm decays. Thus, the observation of a larger than expected effect in charm could indicate new physics.

1.2. Statistical Considerations in the Measurement of CP Asymmetries

If the probability of getting two states which define the asymmetry (labelled + and −) is

$$P_{\pm} = (1 \pm a)/2$$

then the accuracy obtained for the asymmetry a by observing N total decays is:

$$\sigma_a = \sqrt{\frac{1 - a^2}{N}}$$

For even rather large values of a, such as 0.5, it is a good approximation to take

$$\sigma_a \approx \frac{1}{\sqrt{N}}$$

There are several effects, called 'DILUTION effects', which cause the observed asymmetry to be different (lower) than ACPV, which is the actual CP-vioating parameter, and which also reduces the sensitivity for measuring CP violation relative to $\frac{1}{\sqrt{N}}$.

One such is effect comes from the fact that ACPV is not the asymmetry itself but the amplitude of the oscillation that produces it. If one integrates the time dependent asymmetry, one gets

$$\text{Asym}_{t-int} = ACPV \times \frac{x}{1 + x^2} = ACPV \times D_{t-int}$$

The error on the ACPV determined from the time-integrated asymmetry will therefore be

$$\sigma_{ACPV,t-int} = \frac{1}{D_{t-int}\sqrt{N}}$$

The quantity D_{t-int} has a value of about 0.47 for B^o where $x = \Delta m/\Gamma$ is ~ 0.7.

One might ask how much better one does with a fit to the full time-dependent distribution. The answer is not much! The factor goes to around $D_{t-dep} = 0.53$.

Other dilution effects arise from the need to 'tag' the initial flavor of the B whose decay is being measured. That is most often done by observing some property of the other B in the event – the so-called away side B. Tagging can be determined from the sign of an away side lepton from a B-semileptonic decay; from the sign of the away side K-meson; from the charge of the away side B-jet; etc. Every one of these methods can produce an incorrect tag. For example, if the away side particle is a B^o, it can mix before it decays. If the mistag probability is w, it can be shown that the 'dilution' is $(1 - 2 \times w)$. The tagging efficiency ϵ_{tag} and the dilution, D_{tag}, enter the denominator of the sensitivity calculation as $\sqrt{\epsilon_{tag}} \times D_{tag}$ The quantity $\epsilon_{tag} \times D^2_{tag}$ is often referred to as the 'tagging power' or effective efficiency of a particular tag.

Rolling all these considerations up, the error on the asymmetry amplitude, ACPV, is given by the formula

$$\sigma(ACPV) = \frac{1}{D \times \sqrt{N \times \epsilon \times BR}} \tag{5}$$

where

- **N** is the effective number of produced B's of the parent species of interest (in most cases, B^o's);
- **BR** is the branching fraction into the final state of interest;
- ϵ is the overall efficiency including the tag and including any time or detachment cuts; and
- **D** is the 'dilution factor' which includes the effect of integration (or shape dependence if a time dependent analysis is used), away side mixing, muon misidentification, and other problems, which result in mistakes in the tagging. This can be written

$$D = D_{t-int} \times D_{t-res} \times D_{mix} \times D_{mistag}$$

This is for the idealized case of NO BACKGROUND under the signal. If there is significant background, then one must replace N by 'N_{eff}' where

$$N_{eff} = N \times \frac{S}{S + N} \tag{6}$$

where S is the number of true signal events and N is the number of background events.

The large number of efficiency and dilution factors, each hard to predict, makes the estimation of the uncertainty very sensitive to optimism or – stated differently – not very robust.

2. Comparison of B-Reach Potential of Various Experiments

Since many of the decays discussed in the previous section have small branching fractions, it will be necessary to produce a large number of B's in order to study CP violation with reasonable statistics. At a particular accelerator/storage-ring, the two quantities that the determine the number of produced B's are the production cross section and the luminosity. Table 1 shows the number of $b-\bar{b}$ pairs produced per year at the machines that are relevant to future B experiments.

e^+e^- machines produce relatively modest numbers of $b-\bar{b}$ pairs. However, they offer a very clean environment for studying B decays and very high efficiency is possible. The kinematics of the events is highly constrained. For example, if one runs on the Υ(4S), about

Table 1
Luminosity assumptions, cross sections, and rates of produced B's

facility	luminosity	$B-B$ cross section	luminosity per year	$B-B$ pairs per year
CESR II ($\Upsilon(4S)$)	4×10^{32}	$1.15nb$	$4.0fb^{-1}$	5×10^{6}
LEP	1.6×10^{31}	$7.0nb$	$0.16fb^{-1}$	1×10^{6}
FNAL Run I	1×10^{31}	$100\mu b$	$0.1fb^{-1}$	5×10^{9}
e^+e^- ($\Upsilon(4S)$)	3×10^{33}	$1.15nb$	$30fb^{-1}$	3×10^{7}
e^+e^- $\Upsilon(5S)$	3×10^{33}	$0.1nb$	$30fb^{-1}$	3×10^{6}
FNAL [1] Run II	2×10^{32}	$100\mu b$	$2.0fb^{-1}$	1×10^{11}
LHC [2]	1.5×10^{32}	$500\mu b$	$1.5fb^{-1}$	4×10^{11}

25% of all the events have $b-\bar{b}$ pairs. Moreover, the b events are of only two types – $(B^o\bar{B}^o)$ or (B^+B^-). The total energy of the event and the energy of each B in the center of mass is known. This produces a very favorable situation – high efficiencies for reconstructing the decays can be achieved and high tagging efficiencies with low dilution are possible. Continuum events can easily be recognized by well-established methods and do not contribute to the backgrounds. Triggering is easy – one only has to reject purely electromagnetic events. The full rate of hadronic events is only of order of 10 hz at design luminosity so, in principle, all these events could be recorded.

The estimated sensitivity achieved for some key measurements per year of running, which results in an integrated luminosity of 30fb^{-1}at design, is shown in table 2[6]. It remains to be seen whether all these signals can be successfully observed with good signal to background ratios.

On the other hand, the Υ(4S) only allows one to address B_d and B_u decays. The situation on the Υ(5S), where B_s's are produced is not very favorable – the cross section is at least a factor of ten lower and the background is higher. For this reason, many B physics topics of interest, such as detailed B_s mixing and decay studies, b-baryon studies, studies of B_c mesons, and sensitive searches for rare and Standard Model forbidden decays are either difficult or impossible.

The main selling point for hadron colliders is the large B cross section and the ability to achieve very high luminosities:

Table 2
Estimated Sensitivity for $\sin 2\beta$ and $\sin 2\alpha$ for an integrated luminosity 30 fb^{-1}.

Final State	BR	$\sin\phi$	σ
$J/\psi K^o_s$	0.5×10^{-3}		0.10
$J/\psi K^o_L$	0.5×10^{-3}		0.16
$J/\psi K^{*o}$	1.6×10^{-3}		0.19
D^+D^-	6×10^{-4}		0.21
$D^{*+}D^{*-}$	7×10^{-4}		0.15
$D^{*\pm}D^{\mp}$	8×10^{-4}		0.15
Combined		$\sin 2\beta$	0.06
$\pi^+\pi^-$	1.2×10^{-5}		0.20
$\rho\pi$	5.8×10^{-5}		0.11
$a_1\pi$	6×10^{-5}		0.24
Combined		$\sin 2\alpha$	0.09

1. The Tevatron Collider, running at a luminosity of 10^{32} produces $\sim 5\times10^{10}$ b-pairs/'Snowmass year'. This is to be compared with $\sim 3\times10^{7}$ at an e^+e^- symmetric or asymmetric B factory running on the $\Upsilon(4S)$ at a (design) luminosity of 3×10^{33};

2. The Tevatron Collider constitutes a **'Broadband, High Luminosity B Factory'**, which simultaneously provides access to B physics for B_d and B_u, B_s, b-baryon, and B_c states. This permits the kind of comprehensive attack on B-physics issues that is needed;

3. Plans are beginning to take shape to increase the luminosity of the Tevatron to 10^{33} although not all of it may be useful since the experiment may be rate limited;

4. The cross sections at the LHC are higher than those at the Tevatron by at least a factor of 5 and the luminosity should not limit the sensitivity of the experiment in any way.

The prices of the high rate and 'inclusivity' offered by the hadron colliders are:

- The B events are accompanied by a very high rate of background events;

- Even in the B events of interest, there is a complicated underlying event and one does not have available the stringent constraints that one has when running on the $\Upsilon(4S)$ at an e^+e^- collider;

- The B's are produced over a very large momentum and angle range.

These lead to questions about the overall triggering efficiency, tagging efficiency, reconstruction efficiency,

[1] experiment (BTeV) rate limit
[2] experiment (LHC-B) rate limit

and background rejection achievable at hadron colliders. These questions must be answered to convince people that B physics at the sensitivity required for CP violation studies can be done at the Tevatron or the LHC.

It should be noted that the big edge in luminosity at hadron colliders means that the experiments do not have to be as efficient as e^+e^- experiments to be competitive. If they were only 1% as efficient, they would still have a big advantage in statistics.

3. B Physics at CDF – Current Status and Implications for Next Tevatron Collider Run

The next run of the Fermilab Tevatron Collider, usually referred to as Run II, starts towards the end of 1999 and has as a goal an integrated luminosity of more than **2 fb^{-1}**.

To detect CP violation in $B^o \rightarrow \psi K^o_s$ and other states via a tagged, time dependent technique, one needs:

- to reconstruct the final state with good signal to noise;
- to measure the time dependence; and
- to tag with known efficiency and dilution factor.

CDF has used its RUN I data set to do excellent B-physics and, in the course of this, has developed many of the tools and techniques needed to look for CP violation. Using the information obtained from RUN I, it is possible to make good projections of what can be achieved in RUN II. Below, we show how CDF has demonstrated each of the three crucial capabilities required to explore CP violation.

CDF is not a dedicated B-physics experiment so its trigger has not been optimized for efficiency on B mesons. Nevertheless, many B decays either involve leptons, on which they do trigger, or are accompanied by leptons from the semileptonic decays of the second B in the event. Figure 3 shows a signal for the decay $B^o \rightarrow \psi K^o_s$ where $\psi \rightarrow \mu^+\mu^-$ and $K^o_s \rightarrow \pi^+\pi^-$[7]. This state is the 'gold-plated' decay mode mode for observing an asymmetry that determines $\sin 2\beta$. The figure shows the largest sample of reconstructed ψK_s, about 250 events, from any experiment in the world. It has very loose selection cuts. The signal to background is already better than 1:1. It can be improved by requiring more significant separation between the ψ and the primary vertex.

CDF is the first hadron collider experiment to have successfully implemented a silicon vertex detector, called the SVX. With this detector, they have been able to separate the primary interaction vertex and the vertices from b-quark decays. This capability has enabled them to make some of the world's best measurements of the lifetimes of several particles containing b-quarks, including B^o, $B^\pm$, B_s, and Λ_b. Figure 4 [9] shows the proper time distributions for B^o's reconstructed through the 4 decays: ψK^o, ψK^{*o}, $\psi' K^o$, and $\psi' K^{*o}$.

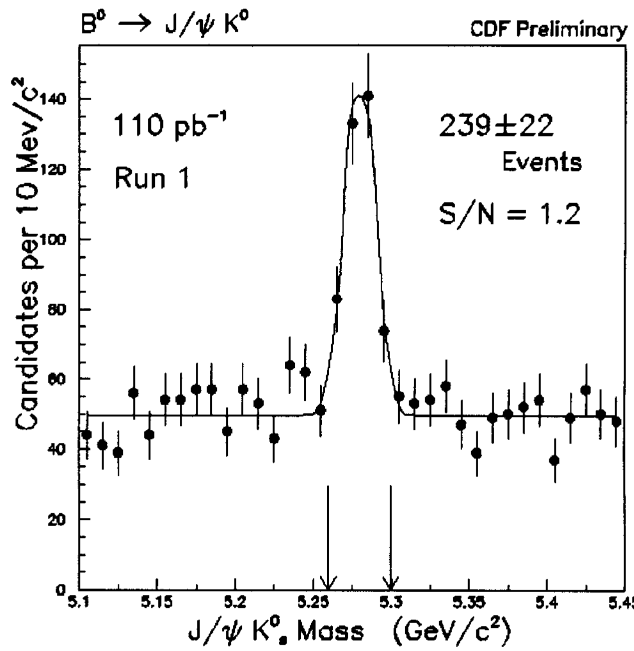

Figure 3. Invariant Mass Distribution for ψK_s from CDF Run I data.

A summary of CDF lifetime results and a comparison with results from LEP, shown in Fig. 5[8], demonstrate CDF's ability to measure the proper lifetime of decaying b-hadrons.

The final capability that must be demonstrated is the ability to tag the flavor of the decaying B^o. In e^+e^-machines running on the $\Upsilon(4S)$, there are many constraints which help one understand what was actually produced in a given event and 'effective' tagging efficiencies of 30% or more are expected. In hadron colliders, there are few kinematic constraints. Tagging was believed to be the 'Achilles' Heel' of hadron collider experiments but again, CDF has made significant progress in understanding how to tag efficiently. They have used several different techniques and have approached an effective tagging efficiency of 3% for Run I data and hope to double this for Run II. If additional particle identification capability can be installed, the total efficiency may even approach 8%. Table 3 shows the various methods used in the Run I analysis and their 'effective' efficiency, taken to be the product of the efficiency and the 'dilution factors' squared.

Same-side tagging is a relatively new method. It ex-

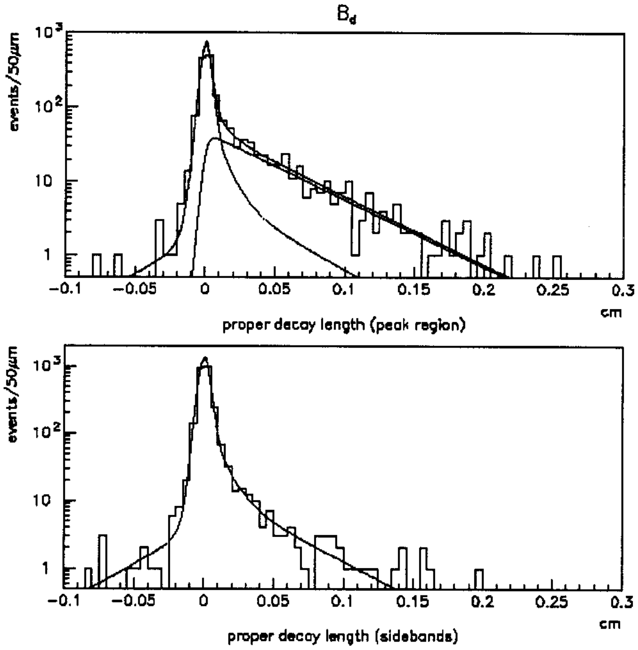

Figure 4. Proper decay length for (upper plot) B^o signal region and (lower plot) B^o mass sidebands.

Table 3
'Effective' Tagging Efficiency, ϵD^2, for various techniques used by CDF for Run I data analysis and projections for Run II

Tagging Method	ϵD^2 Run I	ϵD^2 projected Run II
Away-side lepton	~1%	~1.7%
Away-side Jet charge	~1%	~3%
Same-side π charge	~1.5%	~2%
Away-side K charge	N.A.	~2%

ploits an isospin correlation which comes from the fragmentation process as the bare b-quark 'dresses' itself under the influence of the color force. This method was first demonstrated by ALEPH and OPAL at LEP[10] and by CDF.

CDF has brought all these capabilities together to carry out a time-dependent study of $B^o - \bar{B}^o$ mixing[11]. The data are shown in Fig. 6. Here, the 'signal' is the presence of a reconstructed vertex with a D-meson (D^o, D^+, or D^{*o}) plus a lepton. The charge of the lepton gives the flavor of the B and the charge of the D gives the charge of the B. The 'tag' is the 'same-side pion charge'. The lower plot shows the asymmetry, $\frac{N_{opposite-tag}-N_{same-tag}}{N_{opposite-tag}+N_{same-tag}}$, for the B^o. This should be given by $\cos x_d \tau$ so the value of x_d can be extracted from the clear oscillation that is observed. The top plot shows the same analysis applied to the B^+, where

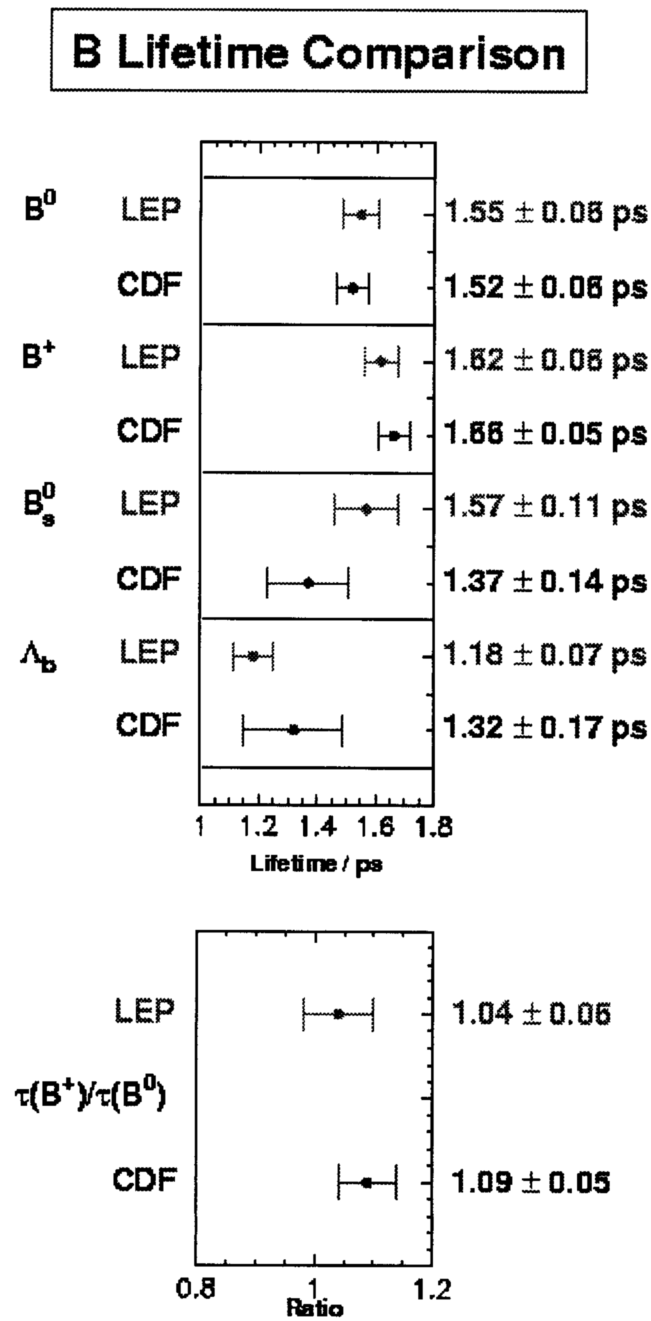

Figure 5. Lifetime Results for (upper plot) B^o, B^+, B_s, and Λ_b and (lower plot) ratio of B^+ to B^o lifetimes from CDF and LEP.

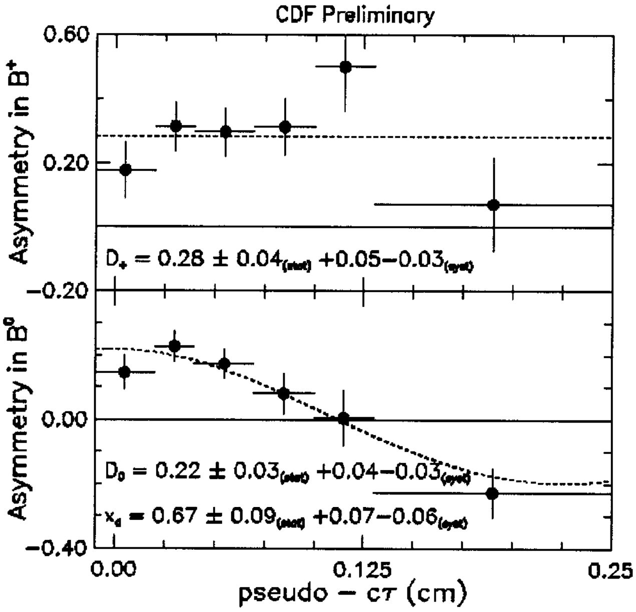

Figure 6. Asymmetry vs pseudo-decay length for (upper plot) B^+ signal and (lower plot) B^o signal. The lower plot shows a clear oscillation signal for the B^o. The top plot shows no evidence for flavor oscillation in a charged mode and provides a check on the analysis.

no time dependence is expected and provides a systematic check. The amplitude of the oscillation gives a measurement of the dilution factor.

Based on the experience from the Run I data analysis and the anticipated integrated luminosity of 2 $fb^{-1}$for Run II, CDF projects the following sensitivities[12]:

$$\sin 2\beta = 0.07 \quad (7)$$
$$\sin 2\alpha = 0.10$$

If all CDF's planned improvements in vertexing and triggering produce the expected the results, their sensitivity will be signficantly better. It is clear that CDF will be a contributor to the first round of investigations of CP violation in B decays. D0 also has similar capabilities for decays involving J/ψ's.

4. The 'Precision' CP Phase

4.1. The Case for a New Generation of Precision CP Experiments in B-Physics

It is highly desirable, even necessary, to check the consistency between the length of the sides and the angles of the CKM triangle. If there is other physics outside the Standard Model, the reactions described above do not necessarily form a triangle. This consistency check should be carried out to very high accuracy.

In fact, it may be quite a challenge to make even a rather qualititative check of the CKM triangle. It will be difficult to measure all three angles. γ may be very hard because there are no experimental signatures that are 'easy' at e^+e^- machines. Also, the extraction of α has run into theoretical complications. It is not clear that $B^o \to \pi\pi$ actually measures α unless one assumes that the Standard Model CKM triangle relation is true. Moreover, it has long been known that a sizable Penguin diagram contribution to the $B^o \to \pi^+\pi^-$ could disturb the simple relation to CKM phases. A recent comparison by CLEO of the ratio of $B^o \to K\pi$ which is mainly a Penguin decay to $B^o \to \pi\pi$ which can have both spectator (V_{ub} suppressed) and Penguin contributions, seems to indicate a bigger Penguin amplitude than expected[13]. This means that α may not be obtainable by the 'classic' mixing-induced process without additional studies. The CLEO result also indicates that the branching fraction of the B^o to $\pi^+\pi^-$ may be quite small, making the measurement of the asymmetry even more difficult.

It is also important to measure B_s mixing since this gives information directly on V_{ts}. The decay $B_s \to \psi\phi$ is expected in the Standard Model to have a very small asymmetry. This needs to be confirmed. Many rare decays, such as $B^+ \to K^+\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$, need to be studied both to get alternate methods of measuring the CKM parameters and because they can reveal new physics. Decays such as $B, B_s \to \mu^+\mu^-$ are expected to be very small and therefore provide a large window on new physics.

4.2. Requirements on the Precision CP Experiments

To achieve the goals described above, one must start with very large numbers of produced B's. Hadron colliders will be the only place that can provide substantially more B's for the next generation experiments. That will be true even if the e^+e^- machines find ways to improve their luminosity by a factor of 10. These machines will not be able to compete with hadron colliders in studying B_s, b-baryon, and B_c physics.

The generation of precision B experiments must do a very complete program of rare B physics. It therefore needs to have good performance for a wide range of final states such as: $B^o \to \pi^+\pi^-$, $B \to D^oK$ and $B \to D^o_{cp}K$, $B^o \to D^+D^-$ and $D^{*+}D^{*-}$, various B_s mixing modes, including ψK^{*o} and $D_s\pi$, various B_s CP studies including study of D_sK and $\psi\phi$, a variety of b-baryon modes, B_c modes, rare decays, and many others.

Hadron experiments currently in the works, such as CDF and Hera-B will aim at roughly the same level of sensitivity as the e^+e^- experiments. Hera-B suffers from a low cross section. CDF suffers from low efficiency due to the soft momentum spectra of the produced B's and severe triggering problems.

The requirements for the next generation experiment are:

- ability to run at high luminosity;
- a very efficient trigger for a wide range of 'hadron' only final states and hadronic tags;
- a very high speed, high capacity data acquisition system; and
- an excellent charged particle identification system.

4.3. The Kinematics of B Production at a Hadron Collider

I am now going to describe an experiment called BTeV which is being proposed for the Fermilab Tevatron Collider. It aims to satisfy these requirements by covering not the central rapidity region, $-1.0 < y < 1.0$, but the forward and backward rapidity regions, $1.5 < |y| < 3.5$.

This coverage 'intercepts' the same amount of the total b cross section as a central detector such as CDF but the b-particles have very different properties which lead to a different, and we believe superior, detector design for the next phase.

The motivation for exploring the possibility of detecting forward-produced B's rather than centrally produced ones may be understood from Fig. 7, which shows the correlation between pseudorapidity, η, and $\beta \times \gamma$ of the produced B. $\beta \times \gamma$ is proportional to the decay length. The B's travel much farther in the forward region than in the central region. From the standpoint of detector resolution on vertex separation, this is not necessarily an advantage since the opening angles are smaller but the multiple scattering is definitely less so that overall, the vertex resolution is better. This leads to higher efficiency for the cuts that are required to reject large backgrounds (usually from generic $b-\bar{b}$ production rather than from minimum bias events) and better time resolution, especially for B_s mixing studies.

At the Tevatron, the pseudorapidity distribution for a single inclusive B-meson is reasonably flat for $|\eta| < 2$ and then falls linearly to about $|\eta| \sim 4$, where it is quite small. However, there is an important correlation that is hidden in the inclusive distribution – the 2 B's tend to be produced close together in angle, as shown in Fig. 8. This means that the two B's go in the same direction, either both forward or both backward. A forward or backward spectrometer can be efficient both for the signal B and the tagging $\bar{B}$.

4.4. The BTeV Detector

The detector[14] is designed to address the challenge of performing 'precision' CP (and related) studies at a hadron collider. The key design features of BTEV are:

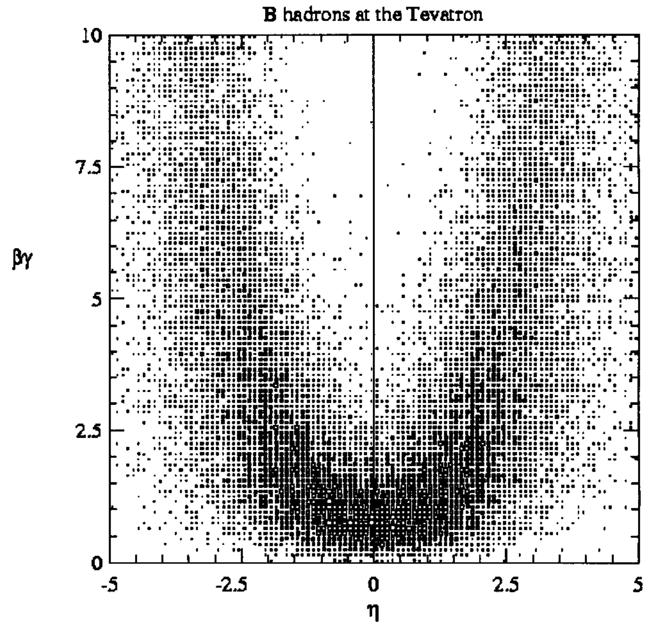

Figure 7. $\beta \times \gamma$ vs pseudorapidity η

- a dipole centered on the interaction region (IR) which gives BTEV an effective 'two arm' acceptance;
- a precision vertex detector based on planar pixel arrays;
- a vertex trigger at Level I which makes BTEV very efficient even for states that have no leptons in them. The tracking system has to be designed together with the trigger electronics to realize the goal of a Level I vertexing trigger; and
- strong particle identification. Especially important is the requirement of very good charged hadron identification. Many of the states that will be of interest in this phase of B physics will only be separable from other states if this capability exists. Also, it will allow for the possibility of kaon tagging. Muon and electron identification are also important for tagging and for studies of decay modes involving leptons.

A schematic layout of the detector is shown in Fig. 9. It is being designed to run in the new C0 experimental hall at the Fermilab Tevatron beginning around 2003 or 2004.

4.4.1. The Central Dipole

The dipole is centered on the IR and has a field integral of 2.6 T-m from the center to each end of the magnet. The dipole gives BTeV effectively two spectrometers and doubles the geometric acceptance. By providing momentum analysis for particles going both

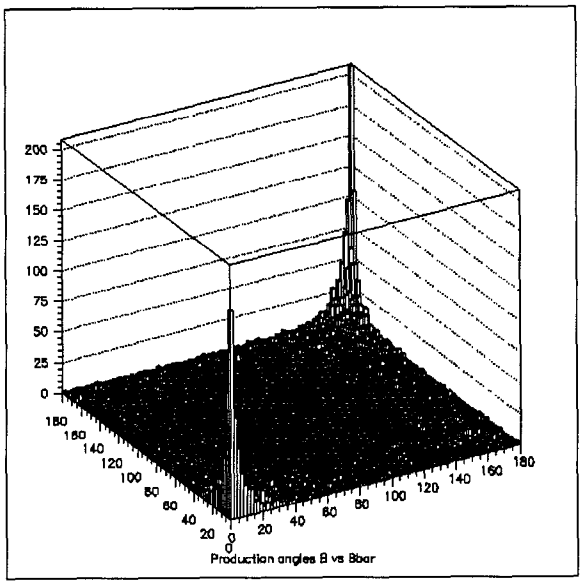

Figure 8. The production angle (in degrees) for a hadron containing a b quark plotted against the production angle for a hadron containing a $\bar{b}$ quark

backwards and forwards from the primary vertex, it improves the number of tracks used to form the primary, which improves the vertex resolution.

4.4.2. Tracking System

In designing a vertex tracking system, one must consider the long interaction region of the Tevatron – $\sigma_z = \pm 30$ cm. This forces one to have a rather long detector. On the other hand, it is actually a positive feature which partially compensates for the long bunch spacing. It may well be possible to work at luminosities higher than the design point of 2×10^{32} because each little section of z is effectively monitored by its own 'quasi-independent' set of planes.

The 'reference detector' has triplets of planes arrayed along the IR separated by about 3.2 cm. Each triplet consists of one wafer that measures the bend view, one that measures the non-bend view, and a third that measures the bend view again. The pixels are 30μm by 300μm. The pulse height is read out and made available to the trigger so that one can derive a crude momentum measurement over three or four triplets. This can be used to reject very soft tracks, whose multiple scattering would make the information

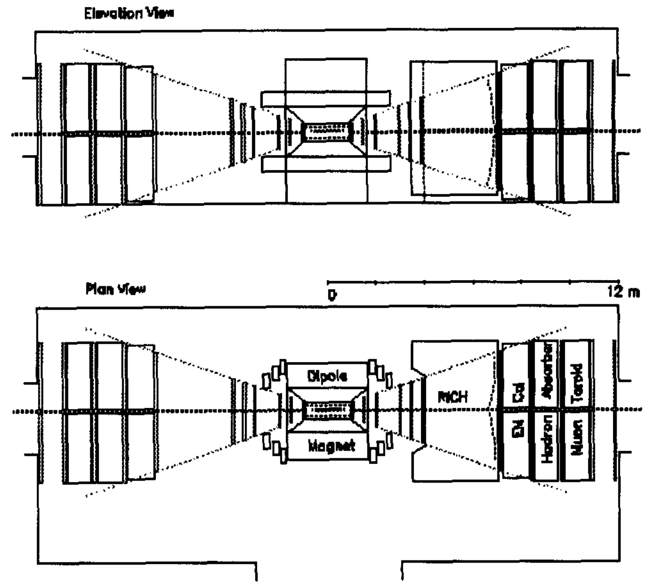

Figure 9. Schematic Layout of the BTeV Detector

from this track confusing to the trigger algorithm.

The implementation of this system will be very difficult. Because the pixels must be made available to the trigger, a custom electronic design is likely to be necessary. Radiation damage is an issue for the inner edge of the detector where the fluence can reach values of 1×10^{14} per year. There are also significant mechanical and thermal issues that must be addressed.

4.4.3. The Level I Vertex Trigger

The proposed program of precision CP measurements requires a trigger whose efficiency is high for those heavy quark decays which can be found offline and which is relatively independent of decay mode. In particular, it must be efficient for final states where the decay products of the signal particle and the tagging particles are all hadrons. BTeV's trigger therefore focuses on the key difference between B events and minimum bias events – mainly the presence of secondary vertices well-separated from the main interaction vertex.

The trigger algorithm has the goal to reconstruct tracks and find vertices in every interaction up to an interaction rate of 10 MHz, corresponding to a luminosity of more than 10^{32}cm^{-2}s^{-1}. The key ingredients of this trigger are:

1. a vertex detector with excellent spatial resolution, low noise, fast readout, and low occupancy;
2. a heavily pipelined and massively parallel processing architecture configured to be well suited to tracking and vertex finding;
3. inexpensive processing nodes, optimized for spe-

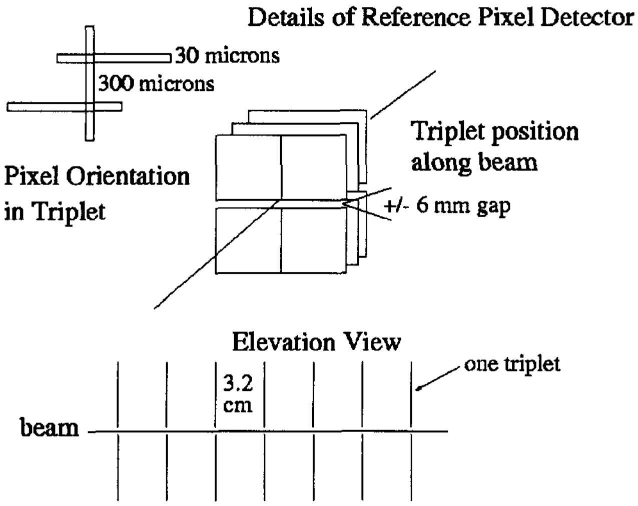

Figure 10. Schematic of the BTeV Vertex Detector

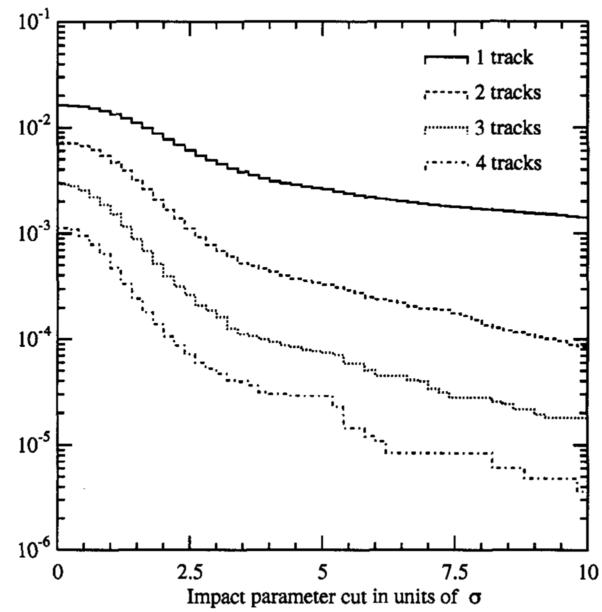

Figure 11. Efficiency of BTeV trigger for 'light quark' events. The number of tracks is the quantity N described in the text. The x-axis is the normalized impact parameter cut, M. The vertical axis is the fraction of all generated events passing the trigger.

cific tasks;

4. sufficient memory to buffer the event data for many beam crossings while the trigger calculations are being carried out; and

5. a switching and control network to orchestrate data movement through the system.

Detailed descriptions of this trigger are available elsewhere[14]. The algorithm has been extensively studied with a hit level simulation. The current plan is for the algorithm to select tracks exceeding a minimum P_t, as measured with the pixel detector alone, to form a primary vertex. Then, the selection is made based on a number 'N' of tracks which miss the primary vertex by a 'normalized' impact parameter exceeding 'M'. With values of N=2 and M$\sim$3, rejection factors of 200 can be obtained for minimum bias events while achieving a 30-40% efficiency on signal events such as $B^o \rightarrow \pi^+\pi^-$. This is quite good for the first level trigger. Moreover, the correlation with events that could in principle be accepted and reconstructed by the spectrometer and could pass reasonable vertex cuts required to reject backgrounds is about 80%. Figure 11 shows the efficiency of the trigger for a range of values of M and N for minimum bias events and Fig. 12 shows the efficiency for $B^o \rightarrow \pi^+\pi^-$.

4.4.4. Particle Identification

Particle identification is based on a gaseous Ring Imaging Cerenkov counter. The radiator will be either C_4F_{10}, with π, K, and p thresholds of 2.5, 9.0, and 17.1 GeV/c, or C_5F_{12}, with thresholds of 2.4, 8.4, and 15.9 GeV/c. This system will give good particle identification from 3 GeV/c to 70 GeV/c. The upper end of the momentum range is sufficient for identifying particles from important two-body B decays such as $\pi^+\pi^-$ and $K^+\pi^-$. The lower end of the spectrum is especially important for charged kaon tagging. An aerogel counter is also being considered to extend the low momentum capabilities of the system.

4.4.5. BTeV Physics Reach

Many of the states that are important to the understanding of CP violation have been simulated with the BTeV design. These include $B^o \rightarrow \psi K_s$,$B^o \rightarrow \pi^+\pi^-$, $B_s \rightarrow \psi K^{*o}$, $D_s\pi$, and $D_s 3\pi$ for measuring B_s mixing, $B_s \rightarrow D_s K$ for measuring γ, and the decay $B^+ \rightarrow K^+\mu^+\mu^-$ as an example of a 'rare' B decay. The studies have been carried out in conjunction with extensive background studies and realistic cuts have been applied to obtain good signal to background. A complete trigger simulation is available and has been used in most of these studies. There have also been studies of the efficiency and dilution factor for muon and charged kaon tagging.

In Fig. 13, we show the signal for $B^o \rightarrow \psi K_s$. The total efficiency for reconstructing this state is 9.1% and the mass resolution in 12.1 MeV/c^2. Employing a set of tags which results in $\epsilon D^2 \approx 10\%$, BTeV achieves an error on $\sin 2\beta$ of 0.04 in one year of running at 5×10^{31}. A similar calculation for $\sin 2\alpha$ gives an error of 0.1 in one year of running (ignoring the possible presence

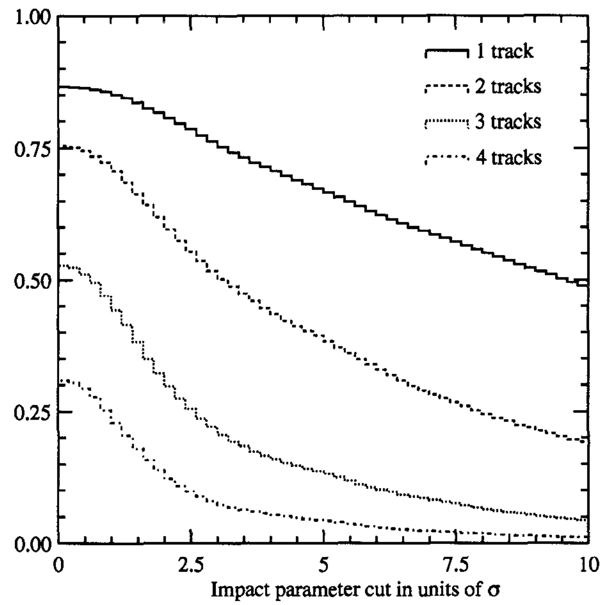

Figure 12. Efficiency of BTeV trigger for $B^o \to \pi^+\pi^-$ events. The number of tracks is the quantity N described in the text. The x-axis is the normalized impact parameter cut, M. The vertical axis is the fraction of generated $\pi^+\pi^-$ events within the spectrometer acceptance which pass the trigger.

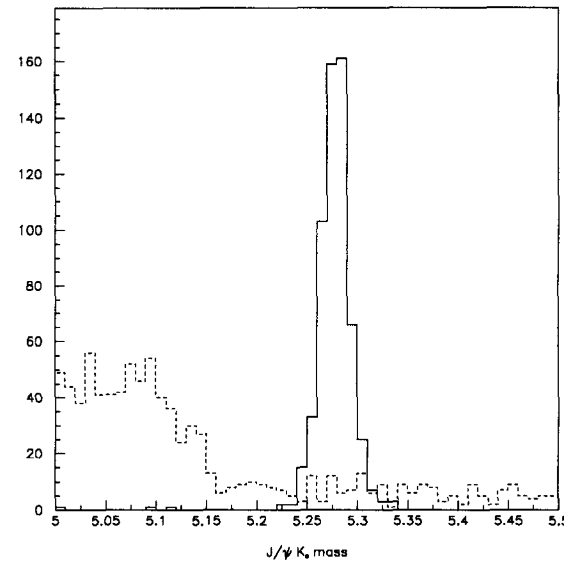

Figure 13. Invariant mass distribution for $B^o \to \psi K_s$ (solid curve) and background (dashed curve).

of a significant Penguin contribution). In Fig. 14, we show the x_s reach of experiment using the final state $B_s \to \psi \bar{K}^{*o}$, which is extremely clean but highly suppressed. Assuming a 'modest' luminosity of 5×10^{31}, BTeV can achieve an x_s sensitivity of 40 in about two years of running. The state $B_s \to D_s\pi$, which is being studied now, will give even higher sensitivity. Studies of methods of measuring γ are in progress. We are also studying various rare decays. A preliminary calculation for $B^+ \to K^+\mu^+\mu^-$ with a branching fraction of 4×10^{-7}[15], gives 10% measurement of the branching ratio in one year of running. The signal to background is expected to be 0.4. However, it is likely that additional cuts which are now under study will improve this further.

5. Concluding Remarks

It is likely that the initial observation of CP violation in B-decays, which should come from the next round of experiments, will lead to more questions and a hunger for a wider range of measurements and for higher precision. Hadron colliders produce the most B's by several orders of magnitude and finally the high precision issues have to be addressed there. There are difficult problems in tracking, triggering, tagging, and particle identification which must be solved to carry out these measurements efficiently. BTeV attempts to address these problems by applying advanced technology.

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REFERENCES

1. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973)
2. L. Wolfenstein, Phys. Rev. Lett. 51, 1945 (1983)
3. J. Christenson, J. Cronin, V. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).
4. For a concise explanation, see H. Quinn, $B^o - \bar{B}^o$ *Mixing and CP Violation in B Decay*, Review of Particle Properties, Phys. Rev. D 50, 1632 (1994).
5. S. Stone, *The BTeV Program*, presented at the Hawaii Conference on B Physics and CP Violation, University of Hawaii, March 24-27, 1997.
6. F. Bianchi, *Status of BaBar at SLAC*, in *Beauty '96*, Elsevier Science B.V. 1996 p 67.
7. The CDF II Detector, Technical Design Report, p 2-73, November 1996.
8. I. Joseph Kroll, *Masses and Lifetimes of B Hadrons*, Proceedings of the 17th International Symposium on Lepton-Photon Interactions, 10-15

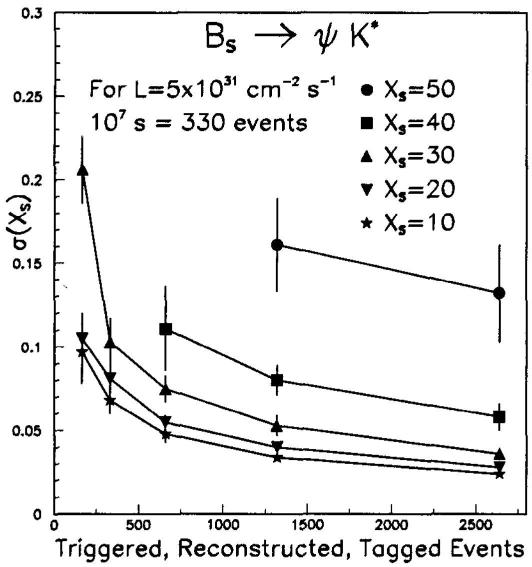

Figure 14. Uncertainty on x_s as a function of the number of triggered, tagged, and reconstructed events for different values of x_s in BTeV.

August, 1995 Beijing China, p 204, published by World Scientific.

9. The CDF II Detector, Technical Design Report, p2-68, November 1996.
10. The OPAL Collaboration, R. Akers et al., Zeit. fur Physik C66, 19 (1995); The ALEPH Collaboration, D. Buskulic et al., Zeit. fur Physik C69, 393 (1996); The ALEPH Collaboration, ***Resonant Structure and Flavor-Tagging in $B\pi^{\pm}$ System Using Fully Reconstructed B decays***, contribution to the International Europhysics Conference on High Energy Physics, Brussels, Belgium,27 July 1995.
11. The CDF Collaboration, ***Observation of $\pi - B$ meson Charge-flavor Correlations and Measurement of Time Dependent $B - \bar{B}^o$ Mixing in $p\bar{p}$ Collisions***, FERMILAB-CONF-96/175-E, July 1996, submitted to ICHEP96.
12. The CDF II Detector, Technical Design Report, p 2-75 and 2-76, November 1996
13. J. Alexander, ***$B \to K\pi$, $\pi\pi$, KK***, Hawaii Conference on *B* Physics and CP Violation, University of Hawaii, March 24-27, 1997.
14. BTeV: An Expression of Interest for a Heavy Quark Program at C0, http://fnsimu1.fnal.gov/btev.html
15. A. Ali, ***Rare B Decays in the Standard Model***, in ***Beauty '96***, Elsevier Science B.V. 1996 p 8.