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B Physics Prospects Beyond the Year 2000

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B Physics Prospects Beyond the Year 2000 *

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Abstract

The search for CP violation in the *b* system will begin with new experiments at BaBar, Belle, HERA-B and perhaps CDF and D0 before the year 2000. The complexity and richness of *B* physics including CP violation suggests that these efforts will require a follow-up experiment. This paper describes a simulation effort to design an experiment for the Tevatron capable of exceeding these first generation experiments.

I. INTRODUCTION

A number of experiments will attempt to observe CP violation in the coming years. These include BaBar and Belle running at asymmetric e^+e^- colliders on the $\Upsilon(4S)$ at SLAC and KEK respectively; HERA-B, a fixed target experiment using HERA's proton beam; CDF and D0 at the Fermilab Tevatron. The primary goal of these experiments is to make the first observation of CP violation in the B system, using the decay $B \rightarrow \Psi K_s$.

The standard model description of CP violation is usually summarized by the unitarity triangle, where the magnitude of products of CKM matrix elements and their relative phases are described by the sides and angles of a triangle respectively. The three angles are conventionally labeled α , β , and γ and CP asymmetries are proportional to the sine of these angles. Testing the standard model can be thought of over-constraining the unitarity triangle by measuring all of its angles and sides. For a more complete discussion of this topic many reviews are available. [1]

The asymmetry measured in $B \rightarrow \Psi K_s$ is related to $\sin(2\beta)$. The first round experiments expect to achieve uncertainties on $\sin(2\beta)$ of 0.10 to 0.20 per year of running. [2] [3] [4]

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They also hope to measure $\sin(2\alpha)$ although their uncertainties will be larger. The measurement of the angle γ is even more difficult requiring measurements of very rare decay modes of the B_d or B^+ , or of the less common B_s .

In addition to the experimental difficulties in constraining the unitarity triangle there can be theoretical difficulties. In the case of $B^0 \rightarrow \pi^+\pi^-$, which we hope to use to measure α , there can be contributions to the asymmetry from γ if the penguin decay is large. Eliminating this problem requires more measurements for example $B^0 \rightarrow \pi^0\pi^0$ or $B^+ \rightarrow \pi^+\pi^0$.

These are just a few examples of the difficulties in measuring CP violation in the b system. For more details on the complexity of fully understanding CP violation please see J. Butler's recent article on B physics at hadron colliders. [5]

CP violation is a complex phenomenon and it will not be solved with the first measurements made in the B system, so how can further measurements be made? The e^+e^- colliders produce about $3 \times 10^7 B\bar{B}$ pairs per year. Since many of the branching ratios to the interesting final states run from 10^{-5} to 10^{-7} , when branching ratios of intermediate states are included, e^+e^- colliders will have very small samples. The e^+e^- experiments already have large acceptance, efficient triggers, and good particle identification, so they are not losing events that can be recovered with a better detector. HERA-B has a small cross section that also leaves them statistics limited. The general purpose collider detectors like CDF and D0 would see about $5 \times 10^{10} B\bar{B}$ pairs at $\mathcal{L} = 10^{32} \text{cm}^{-2}$, but they have severe trigger limitations.

It appears that a new dedicated B experiment at a hadron collider will be necessary to accomplish these second generation CP violation measurements. At CERN there are plans to build LHC-B, a dedicated B experiment at the LHC. This paper reports on an effort to design such a dedicated B experiment for the Tevatron.

II. DESIGN PROCESS

An EOI was submitted to Fermilab to design such a dedicated B detector. Since a second generation CP violation experiment is so challenging, we plan to do a design from scratch and not try to extrapolate from existing detectors. The physics goals of this design are:

- Multiple measurements of all angles of the unitarity triangle,
- B_s mixing,
- Search for B_c and other heavy b flavor states,
- Rare decays.

In order to achieve this type of program, an open but discriminating trigger is needed. Only a secondary vertex trigger seems to satisfy this requirement. Experience at CDF has shown that a good secondary vertex is needed to reject the large combinatoric background in hadron colliders, so a secondary vertex trigger should be efficient for reconstructible decays.

We are following a two prong strategy to design this trigger. One prong is simulation of different detector configurations and B decays to determine the optimum geometry for vertex resolution, which is the topic of the rest of this paper. The other is a hardware development program to design the high-speed, massively-pipelined, compute-intensive trigger.

A. Fast Simulation

To support the simulation effort needed to design a dedicated B physics experiment at the Tevatron, Fermilab's Computing Division has developed a fast simulation program, MCFAST. This program gives accurate momentum and vertex resolutions by calculating the correct covariance matrix based on the number hit detectors and their position resolution and efficiency. It does not simulate the pattern recognition problem, which must be addressed separately. It is capable of calculating occupancies needed in pattern recognition or trigger studies.

MCFAST is similar in its approach to TRACKERR, a program developed at SLAC, but much more flexible. It works for a variety of geometries, which will be more fully discussed in the next section. It can handle tracks from secondary vertices as well as the primary. The primary vertex can be moved event by event and there can be multiple interactions per crossing. Decays in flight and γ conversions are performed. It is not GEANT but it is considerably more complete than the parametric Monte Carlos frequently used for detector design.

MCFAST is fast; simulating $b\bar{b}$ events at the Tevatron in 0.2 to 1.0 second per event on computers like 150 MHz MIPS R4400 chip in the SGI Indy, depending on the geometry. This allows the study of large number of events needed to understand backgrounds.

B. Detector Geometries

The goal of this effort is to investigate a variety of possible detector geometries in a unbiased way. The geometries that we plan to investigate can be characterized by their magnetic field. They include:

- A central solenoid has a solenoidal field at the interaction point. It has its best momentum resolution perpendicular to the beam line.
- A central dipole has a dipole field at the interaction point. It has its best momentum resolution along the beam line.
- A forward dipole is located away from the interaction point. Theoretically, the interaction point is in a zero field region. However, for magnets with large enough acceptance the fringe field near the interaction point probably cannot be ignored. The use of two magnets on either side of the interaction point is a possibility to consider.
- A hybrid detector could mix these geometries to achieve larger acceptance.

For this paper we will consider the central solenoid and the forward dipole geometries. Other geometries will be studied later. Our model of a central solenoid is inspired by CDF. It has a silicon vertex detector with resolution and acceptance very similar to that planned by CDF for RUN II. It also has a central drift chamber, solenoid magnet, electromagnetic and hadron calorimeters, and central muon chambers modeled on the RUN IB CDF detector.

The forward detector has a 28 planes of $x - y$ measuring silicon evenly spaced along the beam. There is a large aperture dipole magnet with $B \cdot \ell$ of 3.0 Tesla-meters. There are 9 stations of tracking before, in, and after the magnet followed by steel and muon chambers.

This model currently lacks any type of particle identification or electromagnetic calorimetry. The tracking system has been tuned to achieve mass resolutions comparable or better than CDF for B decays.

III. SIMULATION RESULTS

There are a variety of B decay modes that we plan to study. The decay $B^0 \rightarrow \psi K_s$ has been studied extensively and will probably be measured before a dedicated B experiment at the Tevatron can run. It is a study that we need to do to compare it to other experiments. The decays $B^- \rightarrow D^0 K^-$, $B^- \rightarrow \bar{D}^0 K^-$ with the D^0 decaying to a CP eigenstate can be used to extract γ , and they are experimentally challenging since there is only one charged track coming from the B vertex. But, for our first study we chose the decay $B \rightarrow \pi^+ \pi^-$. It is considered to be the prototype decay for measuring α . It is also interesting from an experimental point of view. The branching ratio for $B^0 \rightarrow \pi^+ \pi^-$ has not yet been measured but the preliminary evidence from CLEO suggests it will be about 10^{-5} . [6] The signature for this decay is very simple: two oppositely charged tracks with a displaced vertex and an invariant mass equal to the B^0 mass. All the background rejection against random combinations must come from the secondary vertex. While particle identification is vital to reject the backgrounds from B decays like $B^0 \rightarrow K^+ \pi^-$, it has no effect on the random combinations since most particles are pions.

The uncertainty on the measurement of $\sin(2\alpha)$ improves as more data is obtained as expected, but it is worsened by a variety of dilutions such as the background events observed. The expression for the uncertainty is

$$\delta \sin(2\alpha) = \frac{1}{D_{mistag} D_{t-dep} D_{back} \sqrt{\epsilon_{tag} N_{\pi\pi}}}, \quad (1)$$

where

- ϵ_{tag} is the efficiency with which the other B 's flavor is identified;
- $D_{mistag} = (1 - 2w)$, w is the fraction of the time the flavor identification is wrong, whether due to backgrounds, detector imprecision, or mixing of the away side B .
- D_{t-dep} is due to the fact that CP asymmetries that arise due to mixing, sometimes called indirect CP violation, vary with time. If the asymmetry is integrated over time then the measurement of $\sin 2\alpha$ is diluted by 0.47. If a time-dependent fit is used the dilution is 0.53, since at some times there is no asymmetry to measure. [5];
- $D_{back} = \sqrt{S/(S + B)}$;
- $N_{\pi\pi}$ is the number of B 's reconstructed in the $\pi\pi$ decay mode.

Using MCFAST we can find reasonable estimates for N , D_{back} , D_{mistag} for mistags due to $b \rightarrow c \rightarrow \mu$ or decays in flight, and ϵ_{tag} , while D_{t-dep} has been calculated by others.

The BCD group has shown that the dominant background to $B^0 \rightarrow \pi^+ \pi^-$ comes from random combinations in events containing B 's, [7] so our first study uses 40,000 simulated

TABLE I. Comparison of the vertex resolution for $B^0 \rightarrow \pi^+\pi^-$ in the forward and central geometries

Geometry	σ_x or σ_y	σ_z
Forward	$60\mu\text{m}$	$120\mu\text{m}$
Central	$6\mu\text{m}$	$90\mu\text{m}$

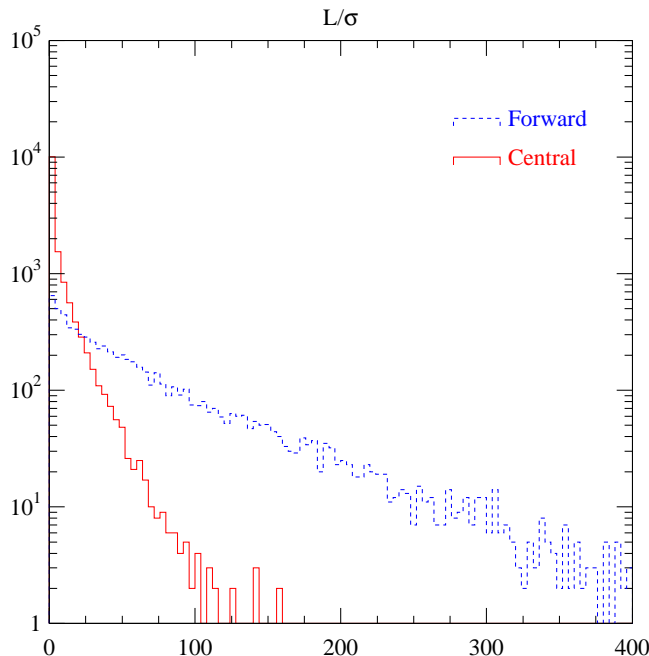


FIG. 1. Comparison of L/σ for the forward and central geometries.

$B^0 \rightarrow \pi^+\pi^-$ decays as the signal and 300,000 simulated generic B events. When the events are simulated the primary vertex is distributed according to the interaction region at the Tevatron. After the tracks are smeared, oppositely charged pairs were fitted to a common vertex. The position resolution for these vertices are shown in table I.

In a forward geometry the most relevant resolution is σ_z while for the central geometry it is the resolution of the distance transverse to the beam which is approximately $\sqrt{2}\sigma_x$. These are almost the same, however the distance traveled by the B 's in the two geometries are quite different. The significance of the vertex measurement is the distance traveled by the B divided by the error on the secondary vertex. The error on the primary vertex tends to be quite small. The distance traveled by B 's in the forward geometry is quite large compare to the distance in the central geometry, so the forward geometry should have an advantage. Figure 1, a plot of L/σ for the two geometries, shows this effect quite clearly.

The analysis applied a series of vertexing requirements to reject background. These are grouped into three classes to illustrate the rejection needed to observe a signal.

1. Vertex exists: All oppositely charged pairs were fit to a a common vertex in space. All good fits were kept.
2. Silicon and displacement: In order to insure that fitted vertex is well measured, each track was required to have at least 4 double sided silicon hits. In addition the vertex

TABLE II. The branching ratio times efficiency for both signal and background. A branching ratio of 10^{-5} was assumed for the signal. All statistical errors are below 1% except for the errors clean up background values which have 100% errors

Cuts	Forward Geometry		Central Geometry	
	Signal	Background	Signal	Background
Vertex	1.9×10^{-6}	1.2×10^{-2}	3.6×10^{-6}	2.2×10^{-2}
Silicon and displacement	1.3×10^{-6}	2.2×10^{-3}	1.1×10^{-6}	1.8×10^{-3}
Clean up	1.2×10^{-6}	1.0×10^{-6}	6.2×10^{-7}	2.0×10^{-6}

was required to have $\chi^2 < 10$ and that $L/\sigma > 8$.

3. Clean up: Fake vertices can arise from two tracks coming from opposite B 's. These are rejected by requiring the reconstructed B^0 point back to the primary vertex. Fake vertices can also arise when tracks from the primary vertex cross tracks from B 's. These are rejected by requiring that π 's not point at the primary vertex.

Table II shows the product of efficiency and branching ratio for both the signal and the background in the two different geometries. This combination takes into account the fact that the signal is very rare compared to the background. A ratio of these quantities immediately gives S/B . For the signal we took the branching ratio to be 10^{-5} and for the background we used 1.0.

The first row of table II shows the results with minimal cuts and the $S/B \sim 10^{-4}$. Applying reasonable vertexing requirements as in the second row yields $S/B \sim 0.5 \times 10^{-3}$, and the very strict vertexing requirements of the third row yield $S/B \sim 1$. The last set of data is statistically limited and we will work on improving the statistics so that we can try to find ways of achieving better S/B values. A $S/B = 1$ increases $\delta(\sin 2\alpha)$ by a factor of 2.

With the loosest cuts the S/B is slightly better for the central geometry than for the forward due the central geometry's larger acceptance. However, as the background is lowered the central geometry loses efficiency more rapidly so by the final cut the forward geometry has better S/B . If this process were to continue, as is desirable, the difference between the two geometries would become more pronounced.

After a signal is observed, it is necessary to determine the flavor of the other B in the event, which is called tagging. Frequently the charge of some other particle in the event is used such as: muons, electrons, or, kaons. If the tagging is not perfect then $\delta(\sin 2\alpha)$ is increased. For this paper only the case of muons have been considered. There are at least three ways to mistag with muons:

1. The decay $b \rightarrow c \rightarrow \mu$ produces a muon with the opposite charge as the b would.
2. If the other B is a B_d or B_s , it can mix before it decays to muon, hence giving the wrong charge. For the mix of B species produced and their known mixing rates, the wrong sign fraction for this effect is 0.125.
3. A pion can punch through the steel and be identified as a muon, or can decay in flight to a muon.

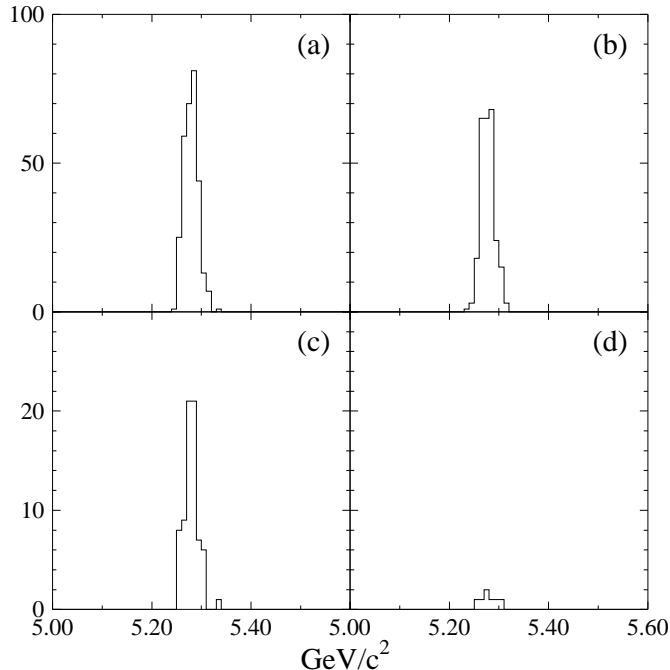


FIG. 2. Comparison of right sign μ tags with wrong sign μ tags in the forward geometry: a) right sign all muons b) wrong sign all muons c) right sign $p_t(\mu) > 2.5\text{GeV}/c$ d) wrong sign $p_t(\mu) > 2.5\text{GeV}/c$.

For case 1 the results can be seen in figures 2 and 3. In figure 2 the forward geometry has a wrong sign fraction of almost 50% without requirements on the muon. However by requiring the muon to have $p_t > 2.5\text{ GeV}/c$, that can be reduced to 10%, but with a loss of tagging efficiency. In the central detector the muon steel causes an effective cut on p_t of the muon, so the initial situation is not as bad as for the forward geometry. After a $p_t > 2.5\text{GeV}/c$ requirement the central is slight worse in wrong sign fraction.

A. Future Simulation Plans

The comparison of the central and forward geometries is not yet completed. A larger statistics sample of background is needed to understand what is needed to achieve S/B better than 1.0. The rejection of $b \rightarrow c \rightarrow \mu$ mistags is currently very simplistic and may be improved. Kaon tagging also needs to be investigated. Other background sources need to be investigated. For example charm particles, which are produced more often, produce displaced vertices and random combinations of these may fake $B^0 \rightarrow \pi^+\pi^-$.

At this stage it is not definitive whether the forward or central geometry is better, but the trends seem to favor the forward geometry. There is a serious caveat about the forward geometry. The magnet needed to achieve the required acceptance and momentum resolution will have substantial stray fields that may degrade the performance of the detector. A central dipole geometry should preserve many of the advantages of the forward dipole geometry and have a uniform field in the vertex region rather than a varying one.

It will also be necessary to benchmark any design against LHC-B. The advantages of

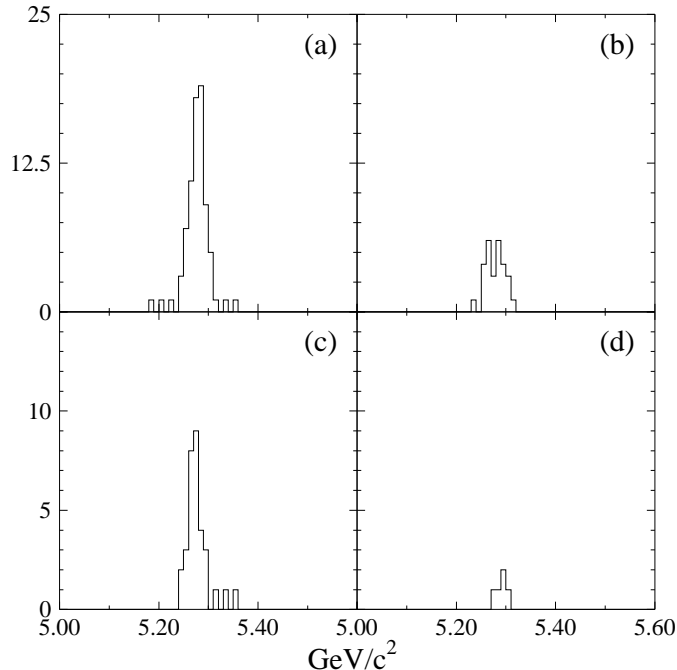


FIG. 3. Comparison of right sign μ tags with wrong sign μ tags in the central geometry: a) right sign all muons b) wrong sign all muons c) right sign $p_t(\mu) > 2.5\text{GeV}/c$ d) wrong sign $p_t(\mu) > 2.5\text{GeV}/c$.

building an experiment at LHC are not as obvious as they may initially seem for B physics. The cross section only increases like the $\log \sqrt{s}$ for b 's. The B 's at LHC are spread out over a larger range of η and are moving faster requiring a larger detector. The advantage due to longer decay lengths is partially compensated by the narrowing of the opening angles of the decays, which makes the vertex resolution worse. The major advantage to using moving B 's is between those that are non-relativistic ($p = 1 - 5 \text{ GeV}/c$) like in a central solenoid detector and those that are relativistic ($p = 10 - 50 \text{ GeV}/c$) like in a forward dipole detector. Only careful studies will answer these questions.

IV. CONCLUSIONS

A program to design a new dedicated B experiment for Fermilab has been started. Using newly developed tools it is possible to calculate reasonably accurate efficiencies, background rejection rates, tagging efficiencies, and wrong sign tagging fractions. These tools have been tested on a comparison of a central solenoid detector with a forward dipole detector for the decay mode $B^0 \rightarrow \pi^+\pi^-$. It is not yet possible or desirable to choose between these two options, as many more physics processes need to be considered as well as other geometries.

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