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Status of BTeV: A Dedicated B Physics Experiment at the Fermilab Tevatron Collider

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BTeV is a program whose long term goal is to carry out precision studies of CP violation, mixing, and rare decays of bottom and charmed quarks in the forward direction at the Fermilab Tevatron Collider. It is planned for the new interaction region, C0, currently being constructed. We describe the techniques, physics reach, and status of BTeV.

1. Introduction

BTeV is a dedicated B physics experiment at the Tevatron Collider. It is expected to begin running in 2004. It is a "Second Generation" experiment to carry out precision studies of CP violation in B and charm decays. We expect experiments that will begin running around the year 2000 to make the first observation of CP violation in B decays, most likely in B^o decays to the "golden mode" of ψK_s. This assumes that e^+e^- machines will approach their design luminosities and experiments at hadron machines will achieve their goals of efficient triggering, tracking, and vertex reconstruction at the anticipated very high luminosities. However, a full program of B physics investigations requires the measurement of the three angles and the three sides of the CKM triangle in order to check for consistency with the Standard Model. Moreover, one needs to make redundant measurements because nearly every measurement, except for $\sin 2\beta$, has problems associated with its interpretation. Because of the limited number of B's produced by e^+e^- machines and in fixed target hadron experiments and the limited efficiency and capabilities of the current generation of hadron collider experiments, which are optimized for high P_t rather than B physics and lack adequate charged hadron identification, there will be much work left to do to see to what degree the Standard Model explanation of CP violation is confirmed and to search for deviations that could suggest new physics.

BTeV intends to extend these first observations to higher precision and to study CP parameters that are beyond the reach of the first generation of experiments. These studies include:

- Measurement of the angle γ by several techniques;
- Precision measurement of the asymmetry in the decay $B^o \to \pi^+\pi^-$;
- Measurement of x_s, the mixing parameter of the B_s;
- Measurement of CP violation in B_s decays;
- Measurement of the branching fractions of decays which are predicted to be rare in the Standard Model;
- High sensitivity searches for decays which are 'forbidden' within the Standard Model and whose observation would indicate new physics; and
- The search for CP violation and mixing in charm decays.

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This is a difficult program which will challenge the ingenuity of experimenters and theorists for many, many years. In the end, only hadron colliders make enough B's to complete it. BTeV will contribute to this program by exploiting the large number of B's produced by the Tevatron to surpass the sensitivity of e^+e^- storage rings; and by emphasizing the forward rapidity region, some unique aspects of the Tevatron, and state of the art tracking, triggering, and particle identification to exceed the reach of other hadron collider experiments.

Table 1
Properties of the Tevatron as a Source of B and charmed Hadrons

parameter	value
Luminosity	2×10^{32}
b cross section	100μb
b-pairs per 10^7 seconds	2×10^{11}
b fraction	10^{-3}
charm cross section	$> 500\ \mu b$
Bunch spacing	132 ns
Luminous region length	$\sigma_z \approx 30\,$cm
Luminous region width	$\sigma_x, \sigma_y \approx 50\mu$m
Mean # interactions/crossing	2.0

2. B Physics at Hadron Colliders

2.1. The Opportunity

The Tevatron, at a luminosity of 10^{32}, produces 10^{11} B-pairs per year. It produces all species of B's: B_d, B_u, B_s, B-baryons of all sorts, and B_c states. It is thus a **Broadband, High Luminosity B Factory.** Cross sections at the LHC are approximately 5 times larger. At both machines, B experiments will be able to have all the luminosity they can handle. At the parton level, B's are made in gluon-gluon collisions which are intrinsically asymmetric so the $B - \bar{B}$ system is boosted in the lab and the lifetime of the B's can be exploited to separate them from background as well as to carry out time evolution studies of mixing and mixing-induced CP violation.

Properties of the Tevatron and of B and charm production relevant to the design of experiments are given in table 1.

2.2. The Challenge

With these advantages come some serious challenges. The B events are accompanied by a very high rate of background events. Only one event in a thousand at the Tevatron is a B pair event. The B's are also produced over a very large range of momenta and angles. Even in the B events of interest there is a complicated underlying event so one does not have the stringent constraints that one has at e^+e^- machines operating on the $\Upsilon(4S)$.

These lead to questions about the triggering, tagging, reconstruction efficiency and background rejection that can be achieved at a hadron collider. On the other hand, with an almost **four order of magnitude advantage in B production**, it is certain that hadron collider B experiments will play a dominant role in the future high precision phase of CP violation studies.

2.3. The Properties of B Production at Hadron Colliders

The cross section for B hadron production at 2 TeV in the center of mass is about 100 μb. The distribution in pseudorapidity, η, is approximately flat from -2.0 to 2.0. From ± 2.0 to around ± 3.5 it falls to zero. The average P_t is a few GeV/c and is not very dependent on η. Near $\eta = 0$, B's are moving slowly and go only a short distance before they decay. At high η, the $\beta\gamma$ of the decays is much larger. The B hadrons live much longer and move far away from the interaction vertex before they decay. At high η, the daughter particles of the B decay have relatively high momenta compared to low η so multiple scatttering is lower, vertex resolution is better, and the analysis cuts required to remove backgrounds are more efficient. The nature of the particle identification problem is quite different at low η and at high η. Figure 1 shows the $\beta\gamma$ distribution of the B hadrons.

The 'flat' rapidity distribution hides an important correlation. If one B hadron is produced at high η the second B hadron is also produced at relatively high η so the two B's are highly correlated in production angle, as shown in Fig. 2.

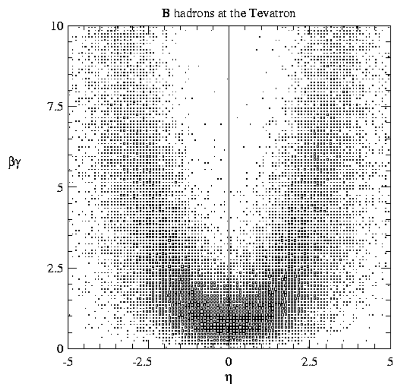

Figure 1. Distribution of $\beta\gamma$ (X axis) vs η (Y axis) for B hadrons

This facilitates flavor tagging in hadron colliders in the forward direction.

2.4. The Technical Requirements for a Program of Precision B Physics at Hadron Colliders

To reach the sensitivity required to achieve the goals listed above, an experiment must have the ability to run at high luminosity. Key features include: radiation hard, highly segmented detectors; a trigger which is efficient for a wide variety of states including those that do not involve any leptons (i.e. all hadronic decays modes with hadronic tags such as kaon tags); superb vertex resolution to achieve high rejection against light quark backgrounds, to carry out time evolution studies, and especially to follow the rapid oscillations of B_s mesons; excellent particle identification to separate decays from background due to 'kinematic reflections' from other B decay modes; and a very high speed, high capacity data acquisition system.

The BTeV experiment, which is being developed to run at the Fermilab Tevatron Collider, possesses these features.

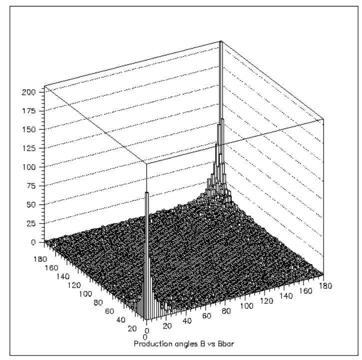

Figure 2. Scatter plot of the polar angle of the B hadron vs the polar angle of the $\bar{B}$ hadron.

3. BTeV: A Dedicated B Collider Experiment

BTeV is a dedicated B collider experiment which is optimize for high precision CP violation and mixing studies. The experiment can also study rare charm decays and D-meson mixing. The BTeV proposal is still under development. An extensive Expression of Interest has been submitted to Fermilab [1]. The R&D phase of the experiment was recently approved by Fermilab. The experiment's goal is to start in the 2003-2004 timeframe.

The key design features of BTeV which give it high efficiency for a wide variety of B decays are:

- A dipole centered on the IR which gives BTeV effectively two spectrometers – one covering the forward rapidity region and one covering the backward rapidity region for a combined coverage of $1.5 < |y| < 3.5$;
- A precision vertex detector based on planar pixel arrays;
- A vertex/impact parameter trigger at Level I which makes BTeV especially efficient for states with no leptons in them.
- Strong particle identification based on a Ring Imaging Cerenkov counter. Many states that will be of interest in this phase

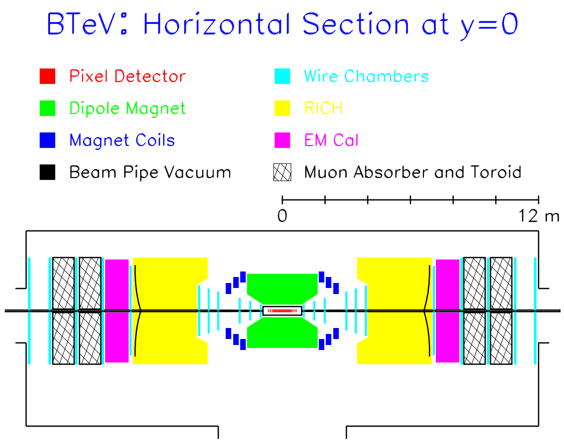

Figure 3. Schematic of the BTeV Dipole Spectrometer

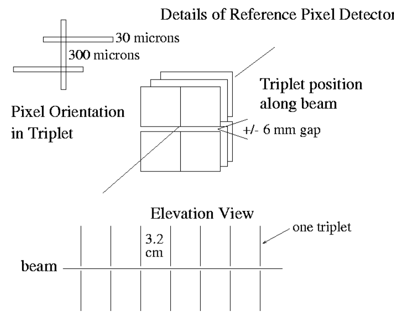

Figure 4. Schematic of BTeV pixel vertex detector

of B studies will be separable from other B states only if this capability exists. It also permits the use of charged kaons for B flavor tagging.

4. The BTeV Spectrometer

A schematic of the BTeV spectrometer is shown in Fig. 3. The spectrometer tracking system consists of a silicon pixel vertex detector and a straw tube outer tracker. Charged hadron particle identification is accomplished with a Ring Imaging Cerenkov counter. Electron identification and photon and π^o reconstruction will be accomplished with an electromagnetic calorimeter. The choice of technology for the calorimeter is still not final. At the end of the system is a muon identifier based on proportional tubes.

4.1. The Tracking System

The vertex tracker consists of planar silicon detectors shown schematically in figure 4. We use silicon pixels because they have excellent spatial resolution, high speed, superior signal to noise, a high degree of segmentation in X and Y which results in low occupancy and intrinsically good pattern recognition capabilities, and are radiation hard. These characterisitcs are very important to BTeV since we will place pixels within 6mm of the beams and will use information from the pixel detector directly in the Level I trigger. The outer tracker is based on 4mm diameter straw tubes.

4.2. The Trigger

The main Level I trigger relies on the presence of secondary decays based on fast reconstruction of the primary vertex and detection of tracks which miss it by significant amounts. The trigger uses a heavily pipelined processing architecture with high speed switches and inexpensive processsing nodes. Hits from the pixel planes are organized into subunits based on azimuthal sectors. In stage 1, station hits are formed from each triplet of planes and these are formed into minivectors. In stage 2, the minivectors are passed to a processor farm which does track finding. Finally, in stage 3, the tracks are passed to a farm of vertex processors. Detailed hit-level simulations of the trigger have been carried out. The trigger efficiency for the decay $B^o \to \pi^+\pi^-$ and the rejection against minimum bias events is shown in figure 5. Here N is the number of tracks exceeding some P_t cut which are required not to point to the primary vertex based on a normalized impact parameter cut, $\frac{b}{\sigma_b}$, whose value is M. For N=2, and M = 3.5, the trigger efficiency is 40% and the probability to trigger on a minimum

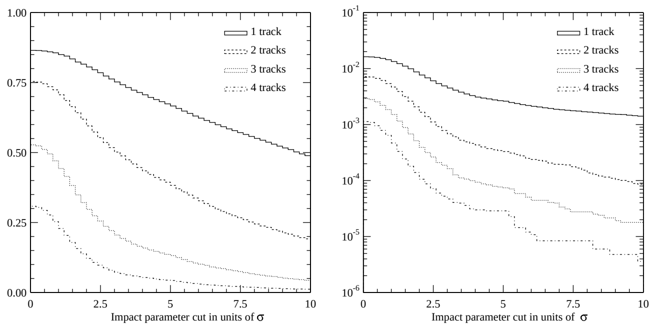

Figure 5. BTeV vertex trigger efficiency for (left) $B^o \to \pi^+\pi^-$ and (right) minimum bias events. In each plot, the differing line styles give the minimum number of tracks N with transverse momentum greater than 0.5 GeV/c required by the trigger to miss the prinary vertex. The horizontal axis gives the normalized cut on the impact parameter which the track must exceed to be declared a miss. The vertical axis gives the efficiency.

bias event is only 5×10^{-3}.

Recently, we have studied the performance of the trigger algorithm when there are multiple interactions per beam crossing. The Level I vertex trigger fires on less than 1% of crossings with interactions even up to a luminosity of 2.5×10^{32} (corresponding to 2.5 interactions per crossing).

4.3. Particle Identification

Particle identification must operate from about 3 GeV/c, for efficient away-side kaon tagging, to 70 GeV/c, for two body decays such as $B^o \to \pi^+\pi^-$. To cover this range, a gas Ring Imaging Cerenkov (RICH) Counter, with possibly an aerogel preradiator to get the lower energy $K-\pi$ separation, is employed.

5. The Physics Reach of BTeV

Using our fast simulation package, MCFAST, we have studied many important final states. The fast simulation has allowed us to generate large samples of background events which are analyzed together with the signal events. In each case, we design cuts that reduce the background to an acceptable level and then apply these to the signal. The efficiencies we quote always reflect the cost of these cuts to the signal and the sensitivities we quote always include the dilution of statistical precision due to the residual background. The following studies have been done: $B^o \to \psi K_s$, $B^o \to \pi^+\pi^-$, $B^o \to K^-\pi^+$, $B^+ \to \bar{D}^o K^+$, $B_s \to D_s^-\pi^+$, $B_s \to D_s^+K^-$, $B^+ \to K^+\mu^+\mu^-$, and studies of a variety of flavor tagging techniques. We will describe results from a few of these studies below.

Table 2
Summary of ϵD^2 for tagging techniques studied by BTeV

Tagging Technique	ϵD^2
$K^\pm$	5%
Muon	2%
electron	1.5%
Jet charge	5%
Same Side	2%

5.1. Flavor Tagging

Studies of mixing-induced CP violation require flavor tagging of the signal B-meson at the moment of its production. This can be accomplished by establishing the flavor of the 'away-side' B produced in the event by the sign of the lepton emerging from its semileptonic decay, the charge of the jet in which it is embedded, or the presence of a kaon from the charmed meson that is usually a daughter product of the B decay. More recently, 'same side tagging (SST)' techniques have been introduced which exploit the correlation of the B flavor with the charge of the closest pion (kinematically). BTeV is capable of using all of these techniques. A summary of the 'tagging power', ϵD^2 (where ϵ is the tagging efficiency and D is the tagging 'dilution factor'), is given in table 2. The value for same side tagging is an estimate based on a preliminary study. We have not yet studied the correlations among all these techniques. We expect that the total ϵD^2 will exceed 10%.

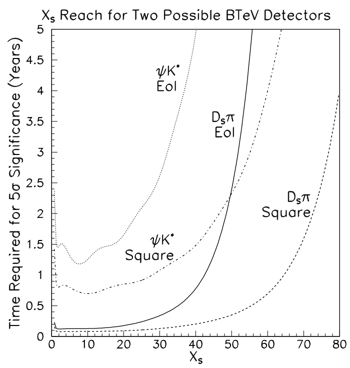

Figure 6. The x_s reach of BTeV using $B_s \rightarrow D_s^{\pm}\pi^{\mp}$. The solid curve indicates, for a given value of x_s, the number of years of running the EOI detector at $5 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to obtain a 5σ effect. The dotted curve gives the same information for $\psi\overline{K}^{*0}$. The other two curves show the improvement obtained by using the square hole design.

5.2. B_s Mixing

B_s mixing has been studied using two decay modes, $D_s\pi$ and the Cabibbo suppressed mode ψK^*. Two configurations of the vertex detector were used: one with a 6 mm slot for the beam, as shown in Fig. 4; the other with a 6mm× 6mm square hole. The $D_s\pi$ mode provides better sensitivity because of its higher branching fraction. The proper time resolution for $D_s\pi(\psi K^*)$ is 52(45) fs in the slot geometry and 38(33) fs for the square hole. The results are shown in Fig. 6

5.3. The angle γ from $B_s \rightarrow D_s K$ [2]

The angle γ can be determined from a study of the time evolution of this decay. The decay can proceed through the two diagrams shown in Fig. 7. Both amplitudes are of the same order so a large interference effect can occur and can give rise to significant mixing-induced CP violation.

There are four time dependent distributions that have to be measured to extract γ:

$$B \rightarrow f \quad \propto \quad \cos^2(\frac{xt}{2}) + \rho^2 \sin^2(\frac{xt}{2}) - \rho\sin(\gamma + \delta)\sin(xt)$$
$$\bar{B} \rightarrow \bar{f} \quad \propto \quad \cos^2(\frac{xt}{2}) + \rho^2 \sin^2(\frac{xt}{2}) + \rho\sin(\gamma - \delta)\sin(xt)$$

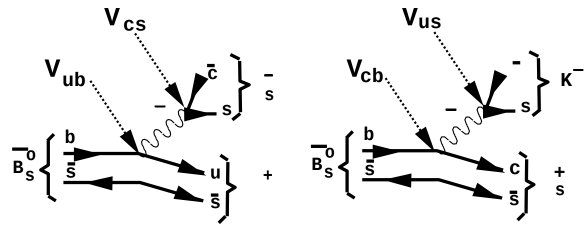

Figure 7. Two diagrams for the decay $B_s \rightarrow D_s K$

$$B \rightarrow \bar{f} \quad \propto \quad \sin^2(\frac{xt}{2}) + \rho^2 \cos^2(\frac{xt}{2}) - \rho\sin(\gamma - \delta)\sin(xt)$$
$$\bar{B} \rightarrow f \quad \propto \quad \sin^2(\frac{xt}{2}) + \rho^2 \cos^2(\frac{xt}{2}) + \rho\sin(\gamma + \delta)\sin(xt) \quad (1)$$

All time distributions above are divided by $|M|^2 \exp^{-t}$ and $M =< f|B >$, $\rho = \frac{|<f|\bar{B}>}{<f|B>}$, and δ is the strong phase shift. We have studied this for the case in which D_s decays into $\phi(K^+K^-)\pi$ and into K^*K. For these decays, the proper time resolutions (slot) are 47 fs and 55 fs, respectively. By measuring all 4 time distributions, we can determine M, ρ, $\sin(\delta + \gamma)$, and $\sin(\delta - \gamma)$. (We assume x_s will have been measured by BTeV or some other experiment) We can then determine γ (up to a twofold ambiguity) to a precision of $\pm 8^o$.

5.4. The angle γ from $B_{d,u} \rightarrow D^o, \bar{D}^o K$ [3]

The decay $B^- \rightarrow \bar{D}^o(K^+\pi^-, K^+(3\pi)^-K^-$ proceeds via a $b \rightarrow u$ transition. It is also possible for $B^- \rightarrow D^o K^-$, where the D^o decays via a doubly Cabibbo suppressed decay such as $K^+\pi^-$, $K^+(3\pi^-)$. This decay has about the same rate us the $b \rightarrow u$ decay. Interference between these two decays yields a measurement of γ. We expect, based on a branching fraction $B^- \rightarrow D^o K^-$ of about 10^{-4}, that we will reconstruct 2400 of these decays where the $D^o \rightarrow K\pi$ and 4200 decays where $D^o \rightarrow K3\pi$. Signal to background is expected to be 1:1. The error in γ in one year of running will be about $\pm 8^o$.

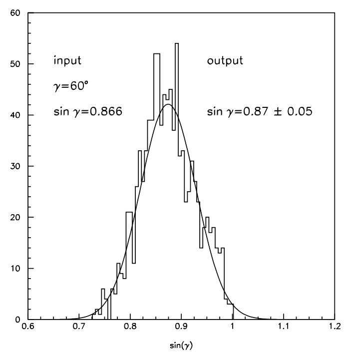

Figure 8. Results of a mini Monte Carlo study of the sensitivity of BTeV to γ as measured from the time dependent study of $B_s \to D_s K$

5.5. The angle γ from $B_d \to K\pi$ vs $B_u \to K^o\pi$ [4]

The decays $B^o \to K^-\pi^+$ and $\bar{B}^o \to K^+\pi^-$ can occur through tree level diagrams containing V_{ub} or Penguin diagrams of the $b \to s$ type. The decay $B^\pm \to K^o\pi^\pm$ involves mainly the Penguin decay. Measurement of these two decay rates are combined to give the quantities:

$$R = \frac{\Gamma(B^o \to K^+\pi^-) + \Gamma(\bar{B}^o \to K^-\pi^+)}{\Gamma(B^+ \to K^o\pi^+) + \Gamma(B^- \to K^o\pi^-)}$$
$$A' = \frac{\Gamma(B^o \to K^+\pi^-) - \Gamma(\bar{B}^o \to K^-\pi^+)}{\Gamma(B^+ \to K^o\pi^+) + \Gamma(B^- \to K^o\pi^-)} \quad (2)$$

These quantities are related to γ by

$$R = 1 + r^2 \pm \sqrt{4r^2\cos^2\gamma - A'^2\cot^2\gamma} \quad (3)$$

where r is the ratio of tree to Penguin amplitudes.

There has been some criticism [5] of this technique because of concerns about rescattering and isospin effects. We therefore simply report that we expect about 250,000 reconstructed $K^\mp\pi^\pm$ with a signal to background ratio of 3:1 and 30,000 reconstructed $K^o\pi^\pm$ with a signal to backgound of 1:2 in one year of running at design luminosity.

5.6. Physics Summary

Sensitivities of BTeV for one year of running at 2×10^{32} are:

Measurement	accuracy
x_s reach	>80
CP asymmetry in $B^o \to \pi^+\pi^-$	$\pm$ 0.013
γ using $D_s K$	$\pm 8^o$
γ using $D^o K$	$\pm 8^o$
$BR(B^o \to K\mu^+\mu^-)$	10%
$\sin 2\beta$ using ψK_s	$\pm$0.014

6. Current Status and Schedule

BTeV is being designed to run at the Tevatron in a new interaction region, C0, which is currently under construction and will be completed in October of 1998. BTeV has recently been approved by Fermilab as an official R&D effort whose goal is to design the final BTeV experiment and to conduct all detector R&D for it. The lab has set up a separate effort in pixel R&D. Members of the BTeV collaboration are strong participants in this effort, which has produced its first successful readout chip and has successfully bump bonded it to a pixel sensor array. Specific milestones have been established for the production of a chip which can satisfy the BTeV technical requirements and work is being done on integrated detector designs. The lab has also established an internal group to work with university groups, Fermilab technical divisions, and others to develop the full BTeV program and to submit a full technical design report in about 18 months. BTeV has recently been reviewed by the National Science Foundation Special Emphasis Panel which has endorsed BTeV R&D [6].

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