FERMILAB-Conf-98/007

BTeV: A Heavy Quark Experiment at the Tevatron

P.L. McBride

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

January 1998

Published Proceedings of *Twenty Beautiful Years of Bottom Physics*, IIT, June 29-July 2, 1997

Disclaimer

Distribution

BTeV: A heavy quark experiment at the Tevatron

Patricia McBride

Fermilab, Batavia, IL 60510

Abstract. The Fermilab Tevatron collider is an excellent laboratory for studying the physics of heavy quarks. Large numbers of events containing $c\bar{c}$ pairs and $b\bar{b}$ pairs will be created in $p\bar{p}$ collisions at 2 TeV center-of-mass energy during the next run of the collider. BTeV is an experimental program that has been proposed for the new C0 interaction hall at the Tevatron. The detector, which will have a forward and backward coverage, is designed for the study of rare decays, mixing, and CP violation in the c and b systems. The proposed detector has excellent vertex resolution and will use a Level 1 vertex trigger to collect large samples of interesting events containing charm and beauty decays.

INTRODUCTION

The observation of CP violation in the kaon systems remains one of the most intriguing puzzles of particle physics. The CKM model provides an explanation within the Standard Model for the observed CP asymmetries and predicts large asymmetries in the B sector although CP violation in the B decays has not yet been observed. The BTeV experiment at the Tevatron is designed to measure these predicted CP-violating effects in B decays. BTeV also plans to make high-statistics measurements in the charm sector which will offer an excellent opportunity for observing effects that are outside the Standard Model, since in the Standard Model charm CP violation and mixing are expected to be very small.

There are several experimental facilities which will begin data taking in the next several years that will have the chance to observe CP violation in the B system. It is expected that the first observation will be in the channel $B_d \to J/\psi K_s^0$. The BTeV experiment will thus be a second generation B experiment and will most likely begin data taking after the first observations of CP violation in the B system. The primary goal of the BTeV experiment is to collect large data samples of events with decays of beauty and charm and to make precision measurements of mixing and CP violation and rare decays. The physics goals of a second generation heavy quark experiment are compelling and will yield important information about the CKM matrix [1].

BTeV offers many possibilities for heavy quark physics. BTeV will collect an estimated $10^7 - 10^8$ reconstructed $\overset{(-)}{D^0} \rightarrow K^{\mp}\pi^{\pm}$ charm decays which is a factor of 10 to 100 over the presently fixed target samples. BTeV will also collect large statistics for many B decays. Unlike the case at the e^+e^- B factories, all species of B hadrons, B^0, B^+, B^0_s, b-baryons and B_c mesons, are produced at hadron colliders. One of the primary goals of this experiment is to measure the angles α, β, and γ of the unitarity triangle that is derived from the CKM matrix for the B system. The triangle in the $\rho - \eta$ plane is shown in Figure 1. The sides and angles of the triangle represent Standard Model parameters. Constraints on the triangle are shown in the bottom plot of Figure 1. The angle α is accessible through $B_d \rightarrow \pi^+\pi^-$, the angle β through $B_d \rightarrow J/\psi K^0_S$ and the angle γ through measuring the time dependent asymmetry in the decays $B_s, \bar{B}_s \rightarrow D^{\pm}_s K^{\mp}$ [2] and also through the decay $B^+ \rightarrow D^0 K^+$ [3] [4]. The measurement of the asymmetry in $B_d \rightarrow \pi^+\pi^-$ and the determination of γ will only be possible at experiments with high statistics B samples as well as good particle identification.

The full BTeV detector will have a high resolution vertex detector, a detached vertex trigger, lepton identification and lepton trigger systems, and excellent particle identification. One of the benchmark measurements for the BTeV detector is the precision measurement of B_s oscillations which can be done by measuring the time evolution and determining the mixing parameter $x_s = \Delta M/\Gamma$. The proposed baseline detector has an x_s reach of ≈ 50 in one year of running at a luminosity of $5 \times 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

B-HADRONS AT THE TEVATRON

Following the commissioning of the new Main Injector, the Fermilab collider will produce on the order of 10^{11} b hadrons and 10^{12} c hadrons during each year of running at luminosities of 10^{32} cm^{-2} s^{-1}. Table 1 shows the projections for the running conditions at the C0 interaction region at the Tevatron.

QCD calculations indicate that in the central region at the Tevatron, b's produced are approximately uniformly in pseudorapidity, as seen in plot in the left side of Figure 2. A plot of the $\beta\gamma$ of b quarks produced at the Tevatron is shown on right side Figure 2. Bs produced in the forward region have much larger values of $\beta\gamma$ than those produced with low pseudorapidity near $|\eta| = 0$. That translates into longer decay distances, better vertex separation, higher momentum tracks and hence better time resolution in the forward region. The production angles of the B and $\bar{B}$ hadrons produced in the forward region are highly correlated as shown in in Figure 3. A large number of $b\bar{b}$ pairs can be detected in the angular coverage in the forward (and backward) region which is a great advantage for measurements that require tagging the flavor of the other b.

THE BTEV DETECTOR

The proposed BTeV experiment is a forward collider detector with two arms that cover the angular region from 10 mrad. to 300 mrad. in the forward and backward region. The detector design has been optimized for the new C0 hall which will be constructed at the Tevatron in 1998. The BTeV detector layout for the C0 hall is shown schematically in Figure 4. The baseline design, which is outlined in the BTeV Expression of Interest [5], includes a large central dipole magnet that bends in a vertical plane and a vertex detector containing a series of pixel planes that covers the long interaction region. The dipole

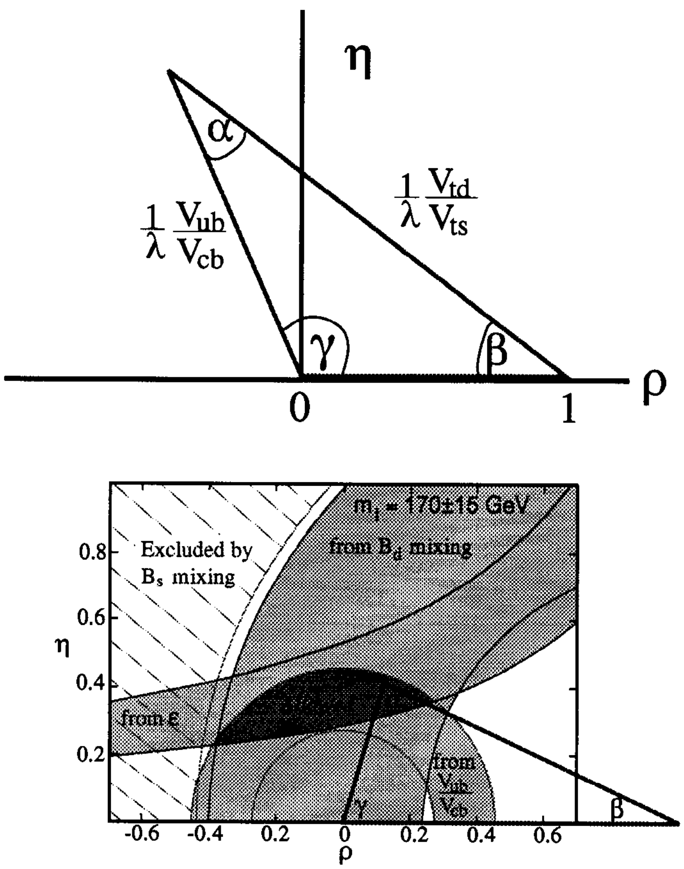

FIGURE 1. ***Top plot:*** Sketch of the CKM triangle showing the usual conventions for the angle α, β and γ. The angles can be determined from measurements of CP violation in B decays. ***Bottom plot:*** Drawing of the $\rho-\eta$ plane showing 1 σ constraints from measurements of ϵ, B_d mixing, and V_{ub}/V_{cb} and the region excluded by B_s mixing measurements.

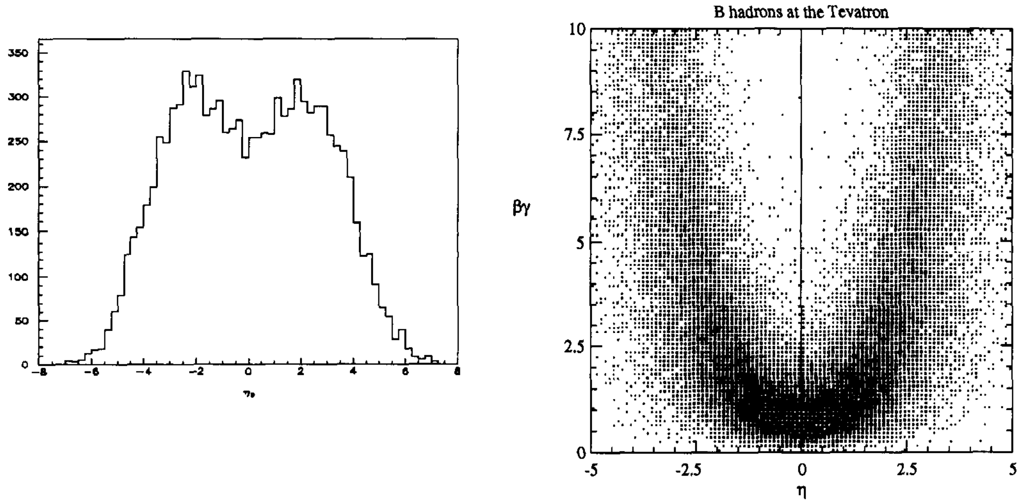

FIGURE 2. Pseudorapidity (η) distribution (left) and $\beta\gamma$ vs pseudorapidity (η) (right) for b hadrons produced at the Tevatron collider.

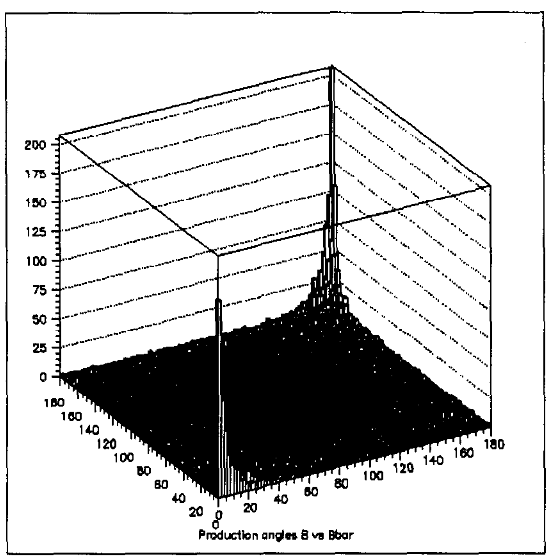

FIGURE 3. The production angle (in degrees) for the b hadron plotted versus the production angle for the the $\bar{b}$ hadron showing the correlation of b and $\bar{b}$ hadrons in the forward region at the Tevatron ($\sqrt{s}$ =2 TeV).

TABLE 1. The Tevatron collider as a b and c source at the C0 interaction region during Run II and beyond.

Luminosity in Run II	$5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$
Luminosity (ultimate)	$2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$
b cross-section	100μb
# of b's per 10^7 sec (Run II)	10^{11}
b fraction	0.2%
c cross-section	> 500 μb
Bunch spacing	132 ns
Luminous region length	$\sigma_z = 30$ cm
Luminous region width	$\sigma_x, \sigma_y = \approx 50$ μm
Interactions/crossing	$< 0.5 >$

magnet for BTeV was used previously in the Fermilab experiment E605 and is made from soft iron that was originally part of the Nevis Cyclotron. The vertex detector will be made from pixel detectors that will be developed for BTeV. Each detector arm consists of a forward tracking system, a Ring Imaging Cherenkov detector, an electromagnetic calorimeter and a muon system. Lepton, dilepton and detached vertex triggers will be used to trigger on heavy quark events. The full BTeV detector will operate in collider mode, but there is also the possibility to use a thin wire target during the initial phase of running.

The baseline design for the vertex detector is shown in Figure 5. The detector is made from 93 layers of pixel detectors, and the individual pixel size is $30\mu\text{m}\times 300\mu\text{m}$. The dimensions are chosen to enhance the resolution and the pattern recognition speed. The planes are grouped in triplets so that small mini-tracks can be formed at each triplet station. This is to help reduce the speed of pattern recognition and permit fast tracking in the vertex detector at the first level of the trigger. In the baseline design the inner edges of the pixel detectors are 6 mm from the beam. While reducing this distance would improve vertex resolution, it also increases radiation damage. The optimization of these effects is under study. The pixel planes will be operating inside the vacuum following a design that was introduced by the P238 Collaboration at the CERN S$p\bar{p}$S [6].

At the Tevatron only a small fraction of interactions will contain a $b\bar{b}$ or $c\bar{c}$ pair. In addition, the interesting branching ratios for the decay modes of interest are very small ($\lesssim 10^{-5}$). Lepton triggers have been shown to work successfully for B physics studies at hadron colliders, however, many of the modes BTeV is interested in studying involve hadronic decays. To be efficient for both b and c decays BTeV must, therefore, have a trigger that is relatively independent of decay mode. The efficiency is optimized if the trigger accepts events that can also be found off-line. The BTeV trigger focuses on the key feature of heavy quark events, the presence of detached vertices, and uses this

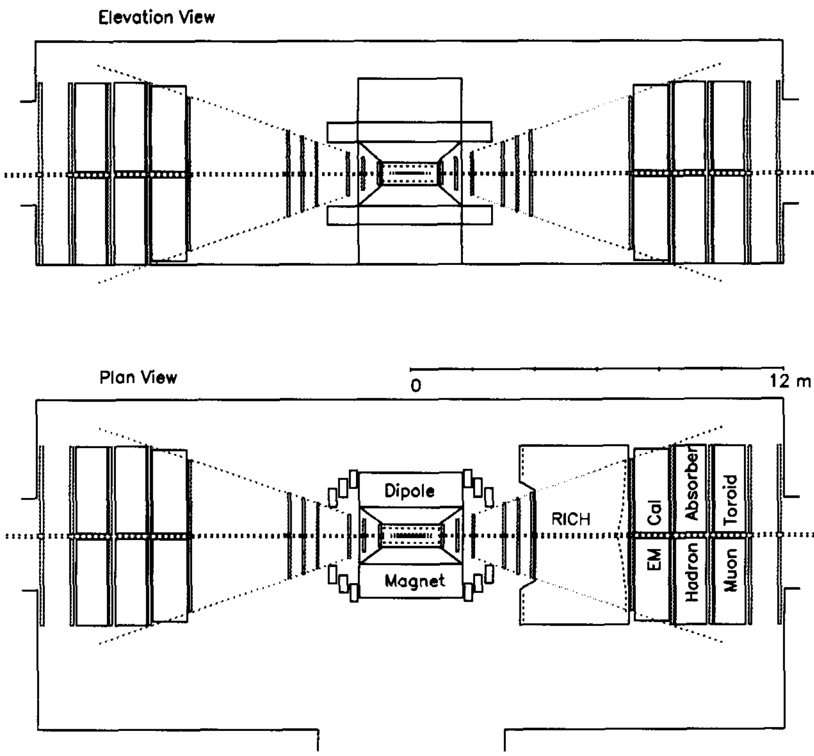

FIGURE 4. Schematic of the BTeV detector showing the central dipole magnet, vertex detector, and the two forward arms each containing a tracking system, a Ring Imaging Cherenkov detector, an electromagnetic calorimeter and a muon system.

at Level 1. Other branches of the trigger will include dimuon triggers and electron and dielectron triggers.

For a heavy quark experiment to operate at the Tevatron, a rejection factor of about 100 for light quark events is needed at Level 1, in order to reduce the data to a manageable amount at Level 2. As stated above, BTeV will use its detached vertex trigger [7] at the first level. One of the key ingredients for the vertex trigger is that the vertex detector have excellent spatial resolution, fast readout and low occupancy. The proposed pixel detector meets these requirements. Sub-event parallelism and a heavily pipelined parallel processing architecture will be used to do the tracking and vertexing in the vertex trigger.

Inexpensive processors and memory are readily available commercially so it is straightforward to buffer the event data while the calculations are performed. The movement of data through the trigger system will be controlled by a switching and control network. A prototype of the vertex trigger processor and switching system is under development at Fermilab.

The reference design for the vertex trigger algorithm is outlined below. Hits in each pixel plane are assigned to a detector sub-unit or ϕ slice. Station hits are formed in a hit processor for each ϕ slice of a triplet pixel detector station. The resulting mini-vectors are sent from the hit processor via a sorting switch to a farm of track processors where the tracking is done. Tracks are then passed to a farm of vertex processors. The primary vertex is found in the vertex processor and tracks with large impact parameter are selected. Momentum information is used in the trigger to exclude low momentum tracks, whose impact parameters are badly smeared by multiple scattering. Preliminary simulation studies show that the reference design for the vertex trigger can achieve efficiencies of approximately 70% for accepted and reconstructed B decays such as $B_d \to \pi\pi$ and rejections of better than a factor of 100 for light quark events [5].

Particle identification will be critical for studying modes such as $B_d \to \pi^+\pi^-$ where the backgrounds from other two body B decay modes are expected to be large. It is useful for tagging since kaons from the other B can be used to flavor tag the signal b. To achieve reasonable separation of kaons and pions over the momentum range of 3 GeV/c $< p <$ 70 GeV/c is needed to accomplish these two goals. The BTeV RICH detector will have a C_4F_{10} gas radiator with $\pi/K/p$ thresholds of 1.6/9.0/17.1 GeV/c to achieve reasonable

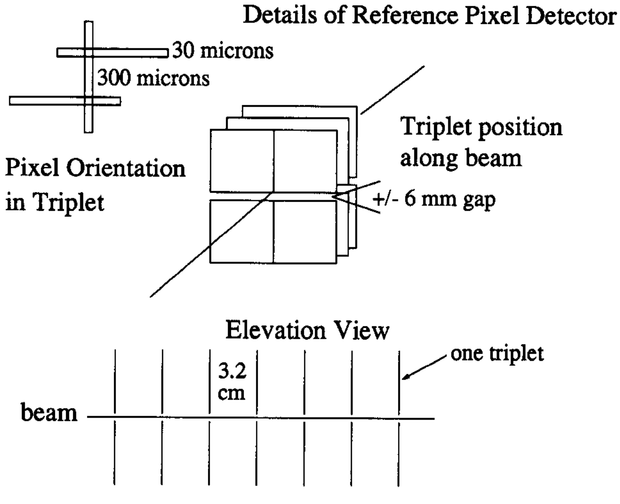

FIGURE 5. Schematic diagram of the BTeV vertex detector. The detector will be made of planes of pixel detectors. In the baseline design, these pixel planes are arranged into a triplet pattern with 31 stations positioned along the interaction region.

separation over this momentum range. Increased capability for identifying low momentum particles could be achieved by adding a thin aerogel radiator at the entrance to the gas RICH. This has been proposed by the LHC-B collaboration for their RICH [8] and will be investigated for use in BTeV.

Downstream tracking chambers are used to provide better momentum measurements for tracks exiting the magnet. They will also provide the only momentum measurement for tracks, such as daughter tracks from K_S^0 decays, that do not pass through the vertex detector. The baseline technology for this detector is planes of straw tubes.

Lepton identification is essential for any heavy quark experiment. The ability to identify electromagnetic final states is an integral part of the BTeV physics program. Electron and photon identification will be done with electromagnetic calorimeters located behind the RICH detectors. Various technologies are under investigation for this detector. Muon identification will be done with a system of iron toroids and muon chambers at the back of each detector arm. Many of the physics goals such as rare decay searches and tagging for CP violation and mixing studies rely on efficient muon identification. The muon system and electromagnetic calorimeter will also be used to provide J/ψ and prompt lepton triggers.

Physics Reach of the BTeV Detector

BTeV will be well positioned to make precision measurements of CP violating and rare decays of b and c hadrons. It will be able to make a competitive precision measurement of the angle β using the "golden" mode $B_d \to J/\psi K_S^0$. In one year of running at nominal luminosity, the uncertainty on sin2β will be $\delta\text{sin}2\beta = 0.042$ [5] with $J/\psi \to \mu^+\mu^-$ only.

A summary of the expected yields for B decay modes of interest for one year of running at a luminosity of $5 \times 10^{31}\text{cm}^{-1}\text{s}^{-2}$ is given in Table 2. The geometrical acceptance, expected trigger efficiency and reconstruction efficiency for final analysis cuts are included in these estimates. For CP-violating asymmetries, the sensitivity can be characterized by the number of untagged events scaled by the effective tagging efficiency ϵD^2, where D is the dilution due to mistags. The combination of lepton and kaon tags gives a tagging efficiency of 15% with a mistag fraction of about 25%, which yields an effective tagging efficiency $\epsilon D^2 \approx 4\%$. Jet charge and same-side tags will increase the sensitivity by improving ϵD^2 to $\approx 8 - 10\%$.

An observed CP asymmetry in $B_d \to \pi^+\pi^-$ provides information on the angle α. The BTeV vertex trigger is an ideal way to trigger on this mode and the RICH provides good separation of the $\pi\pi$ decays from other two body decays of B mesons. The backgrounds in this channel come mainly from $b\bar{b}$ events. Preliminary studies from a sample of 5 million simulated $b\bar{b}$ events indicate that the signal (S) to background (B) ratio ($S/S + B$) will be an

TABLE 2. BTeV event sample sizes after one year of running at luminosity of $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$.

Channel	Observed mode	Untagged events/year	Physics
$B_d \to J/\psi K_s^0$	$\mu^+\mu^-\pi^+\pi^-$	28000	sin 2β
$B_d \to \pi^+\pi^-$	$\pi^+\pi^-$	17000	sin 2α
$B_s \to D_s K$	$\phi\pi K; \phi \to K^+K^-$	2350	sin γ
$B_s \to D_s K$	$K^{0*}KK$	3000	sin γ
$B_s \to D_s \pi$	$\phi\pi^-\pi^+; \phi \to K^+K^-$	17000	x_s
$B_s \to J/\psi \bar{K}^{0*}$	$\mu^+\mu^-K^-\pi^+$	1470	x_s
$B^\pm \to K^\pm\mu^+\mu^-$	$K^\pm\mu^+\mu^-$	300	SM rare decay

important dilution factor if one assumes a branching fraction for $B_d \to \pi^+\pi^-$ of 0.75×10^{-5} [9]. The uncertainty on sin2α from one year of running is expected to be δsin$2\alpha \approx 0.10$ [5] ignoring penguin contributions.

BTeV will have excellent resolution for secondary vertices which translates into good proper time resolution. This makes it an ideal detector for studying B_s mixing since x_s is expected to be large. Current limits on B_s mixing from LEP indicate that $x_s > 15$ [10]. Studies of several decay modes of the B_s [11] have been made in order to understand the sensitivity to B_s oscillations. The decays $B_s \to J/\psi\bar{K}^{0*}$ and $B_s \to D_s\pi$ when fully reconstructed in BTeV give a time proper resolution of ≈ 0.045 ps. For these studies we simulated the baseline BTeV detector using the detector simulation package MCFast [12]. The mixed and unmixed decays of $B_s \to D_s\pi$ for an $x_s = 40$ are shown in the left hand plots of Figure 6. The x_s reach for the mode $B_s \to D_s\pi$ is shown in the right hand plot of Figure 6.

One of the major goals of BTeV will be the measurement of the angle γ. Simulation studies are underway to investigate the reach of the BTeV detector from the time evolution of the decays $B_s, \bar{B}_s \to D_s^\mp K^\pm$ [13]. The sensitivity of the measurement depends on the mixing parameter x_s and on the branching fractions for $B_s \to D_s^\mp K^\pm$ which are not well known. It is clear that good particle identification will be crucial for this measurement in order to separate the signal from the background coming from $B_s \to D_s\pi$.

The physics potential for BTeV is vast and has been more fully documented elsewhere [5] [14] [15]. In addition to the extensive program in the B sector, BTeV plans to collect a high statistics charm decay sample in order to look for CP violation and mixing in the charm sector. The proposed schedule for BTeV calls for first collisions with a partial detector in the C0 hall during Run II. The full detector would then be installed and BTeV would begin running with a luminosity of $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ soon after.

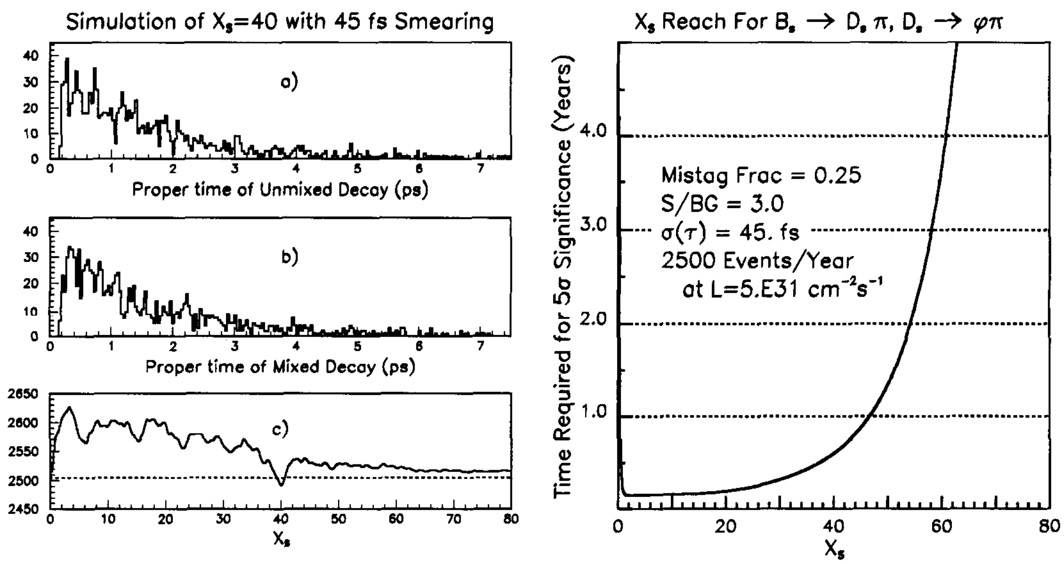

FIGURE 6. Proper lifetime plots of a) unmixed and b) mixed decays for the decay mode $B_s \rightarrow D_s\pi$ for one year of running. Part c) shows the corresponding negative log likelihood as a function of x_s. The right hand plot shows the x_s reach of the BTeV detector using the mode $B_s \rightarrow D_s\pi$.

Acknowledgements

The author would like to acknowledge the work of Penny Kasper, Rob Kutschke, Joel Butler, Paul Lebrun, Mike Procario, Tomasz Skwarnicki, Vince Smith and Kevin Sterner who produced the simulation results for the BTeV Expression of Interest.

REFERENCES

1. N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963); M. Kobayashi and K. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
2. R. Aleksan, I. Dunietz and B. Kayser, Z. Phys. **C54** , 653 (1992).
3. M. Gronau and D. London, Phys. Lett. **B253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. **B265**, 172 (1991).
4. D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997).
5. BTeV: An Expression of Interest for a Heavy Quark Program at C0, BTeV-pub-97/2, http://www-btev.fnal.gov/public_documents/c0_eoi_1.ps, May 1997.
6. J. Ellett *et al.*, Nucl. Instrum. Meth. A 317, 28 (1992).
7. D. Husby, P. Chew, K. Sterner, W. Selove, Nucl. Inst. and Meth. A **383** (1996) 193.

8. R. Forty, CERN-PPE/96-176, Sept. 1996 published in Proc. of the 4th Int. Workshop on B-Physics at Hadron Machines, Rome, Italy, June 1996, F. Ferroni, P. Schlein (Eds.) North-Holland, 1996.
9. M. Procario, BTeV-int-97/10.
10. V. Andreev *et al.* (The LEP B Oscillations Working Group), "Combined Results on B^0 Oscillations: Update for the Summer 1997 Conferences," LEP-BOSC 97/2, August 18, 1997.
11. R. Kutschke, BTeV-int-97/9.
12. P. Avery *et al.*, "MCFast: A Fast Simulation Package for Detector Design Studies," in the Proceedings of the International Conference on Computing in High Energy Physics, Berlin (1977) and http://www-pat.fnal.gov/mcfast/mcfast_docs.html.
13. Penny Kasper, BTeV-int-97/13.
14. J. N. Butler, "Prospects for Heavy Flavor Physics at Hadron Colliders," in proceedings for Frontiers in Contemporary Physics; "Fundamental Particles and Interactions," May 11-16, 1997 at Vanderbilt University, Nashville TN.
15. S. Stone, "The Goals and Techniques of BTeV and LHC-B," in the proceedings of the International School of Physics, "Heavy Flavor Physics - A Probe of Nature's Grand Design," Varenna, Italy, 8-18 Jul 1997.