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Physics Prospects at BTeV

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Abstract

BTeV is a proposed forward collider program at the Fermilab Tevatron dedicated to precision studies of CP violation, mixing and rare decays of beauty and charm hadrons.

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1 Introduction

Although most data on B physics has been collected at e^+e^- colliders there is much interest in doing B physics at hadron colliders because of the large production cross-section. At the Fermilab Tevatron, CDF and D0 have produced many interesting B physics results proving the feasibility of doing B physics at a hadron collider. In the next few years current experiments CLEO, CDF and D0 will begin new runs with upgraded detectors and several new detectors (HERA-B, BELLE and BaBar) will begin data taking. However there are many channels that are beyond the limits of sensitivity of these experiments. In addition, the e^+e^- machines operating at the $\Upsilon(4S)$ cannot produce B_s, B_c or Λ_b.

BTeV is intended to be a next generation high statistics heavy quark experiment. The design of the proposed forward collider detector is optimized for precision studies of beauty and charm decays and is designed to fit in the C0 interaction region of the Tevatron. An Expression of Interest (EOI) was submitted to the Fermilab PAC in May 1997 [1]. In January 1998 BTeV was formally approved as an R&D project and a contract was awarded for the construction of an appropriate collision hall in the C0 interaction region.

2 Physics Goals

The main physics goals of BTeV are the precise measurement of Standard Model parameters including CKM matrix elements and decay constants, and the search for new phenomena beyond the Standard Model. We assume that the angle β of the unitarity triangle will already have been measured, but we will be able to reduce the error. In particular, we will measure the asymmetry in $B^0 \to \pi^-\pi^+$ and the angle γ of the unitarity triangle. Time dependent studies of mixing in B_s decays will lead to the measurement of x_s ($\Delta m/\Gamma$), and we will also measure the width difference $\Delta\Gamma$ between the two CP eigenstates. In the Standard Model CP violating effects are small in the charm sector so this provides an excellent opportunity to search for non Standard Model effects.

3 Detector Design

The Fermilab Tevatron is the highest energy particle accelerator in operation. The new Main Injector will increase the luminosity to $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$. The simulations for BTeV assume a luminosity of $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ which results in a mean number of interactions per crossing of 0.5. At a collider energy of 2 TeV the $b\bar{b}$ production cross section is $\approx 100\mu$b. The Tevatron operating at a luminosity of $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ will yield 5×10^{10} $b\bar{b}$ pairs per year. Eventually we intend to run with a luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ under luminosity leveled conditions [2] which gives an effective factor of 8 increase in the number of events.

The proposed reference detector is a 2-arm forward collider detector ($1.5 < |\eta| < 4.5$)(Fig. 1) There are several advantages of having a forward detector: (i) the higher momentum forward B's have a greater vertex separation - this enables us to have a Level I vertex trigger, helps to reduce background and improves time resolution, (ii) there is room for charged particle identification, and (iii) the strong correlation between the b and $\bar{b}$ production angles in the forward direction means that a significant fraction of events will have both b and $\bar{b}$ in the detector.

The interaction region has a length of $\sigma_z = 30$ cm and we have a pixel vertex detector inside a central dipole field which surrounds the interaction region. This enables a rough momentum measurement on the tracks in the Level I vertex trigger. The layout of the pixel planes is shown in Fig. 2. Triplets of silicon pixel planes will be placed inside the beam pipe, as close as possible to the beam to ensure a large acceptance in the forward direction. The planes are retracted while the collider is being filled and then closed down to leave a gap of ± 6 mm. New simulations indicate a significant improvement in x_s reach if a detector with a square hole, 1.2cm $\times$ 1.2cm, centered on the beamline, is used.

Silicon pixel detectors rather than silicon strips are chosen because of their low occupancy, superior signal to noise, and intrinsically better pattern recognition which enhances the ability to do real-time tracking that is needed for the Level I vertex trigger. The reference detector has pixels $30 \times 300\mu$m but we are studying how much bigger the pixels can be made without degrading the performance. A more detailed account of the continuing pixel R&D effort is given in these proceedings [3]. Downstream tracking is necessary to provide better momentum resolution and to reconstruct K_s's which decay outside the pixel detector. We are considering different technologies including straw tubes.

Charged particle identification is essential to distinguish between final states which overlap in mass, for example $B_d^0 \to \pi^+\pi^-, B_d^0 \to K^\pm\pi^\mp$ and $B_s^0 \to K^+K^-$. In addition, many studies of neutral B mesons require flavor tagging. Our studies show that kaon tagging is a very effective method. The proposed RICH is described in these proceedings [4]. Design studies for a muon detector and electromagnetic calorimeter are also in progress.

An essential component of BTeV is the Level I vertex trigger. The requirements for the trigger are that it must be capable of reducing the event rate by a factor of more than 100 while maintaining a high efficiency for heavy quark events which pass the offline analysis. The trigger is based on having a number of tracks with significant impact parameter with respect to the primary vertex. The reference trigger scheme was developed by the University of Pennsylvania [5] and is currently being refined. The effects of multiple interactions per bunch crossing and secondary interactions in the vertex detector are being studied. Initial results on the performance of the baseline trigger in the presence of multiple interactions are shown in Fig 3. The yield for $B^0 \to \pi^+\pi^-$ is linear in luminosity while the probability for triggering on a minimum bias event is 0.23% up to a luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$ and then rises to 0.40% at a luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ [6].

4 Simulations

Detailed simulations of several physics channels have been carried out to explore the physics reach of the baseline BTeV detector as described above. The results are based on an average luminosity of $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ for 10^7 s and a $b\bar{b}$ cross-section of 100μb. However the integrated life of the experiment will be much longer than 10^7 s, and the detector will be able to run with a factor of 4 higher luminosity. We also plan to run under luminosity levelled conditions which results in an effective factor of 2 increase in luminosity.

Events are generated using Pythia 5.7 and Jetset 7.4 [7]. The heavy quark decays are then modeled through the CLEO decay Monte Carlo QQ. The detector is simulated using MCFAST v2_6 [8], a fast Monte Carlo package developed by the Fermilab Simulation Group for detector design studies. Particle trajectories are traced though simple geometric shapes then tracks are parametrized using a Kalman Filter technique. A covariance matrix for each track is found taking account of multiple scattering and detector resolution. The covariance matrix is used to smear the original track parameters then the smeared track parameters and covariance matrix are stored as a reconstructed track. Hit generation is used for trigger studies.

4.1 Tagging

In order to study neutral B meson oscillations it is necessary to know the flavor of the b quark (b or $\bar{b}$) both at production and decay. Measurements of CP asymmetry in modes such as $B_d \to \pi^+\pi^-$ and $B_d \to \psi K_s$ also require the determination of the flavor of the b quark at the production point. This is known as flavor tagging. "Away-side" tagging methods rely on the determination of the flavor of the other b quark in the event *eg.* from the charge of the lepton in semileptonic decay or from the charge of the kaon produced in the $b \to c \to s$ cascade. Simulations indicate that we can expect an effective tagging efficiency ϵD^2 of $\approx$1.5% for muon tagging and $\approx$5% for kaon tagging. Other tagging methods are being studied.

4.2 Measurement of the B_s mixing parameter x_s

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 $x_s > 15$ [9]. Studies of two different decay modes of the B_s have been made in order to understand the sensitivity to B_s oscillations. The decay mode $B_s \to \psi \bar{K}^{*0}, \psi \to \mu^+\mu^-$. was chosen because it had single 4-prong vertex that could be triggered both with a muon trigger and a secondary vertex trigger. From simulations we expect 220 events (reconstructed, triggered and tagged) per 10^7 s in this mode with S/B=3 and a time resolution of 45 fs [1]. (The yield would increase by at least 50% if the decay mode $\psi \to e^+e^-$ is also used.) Later studies were done with the decay mode $B_s \to D_s\pi, D_s \to \phi\pi, \phi \to K^+K^-$ which has a much larger branching fraction. In this mode we expect 2400 events per 10^7 s with S/B=3 and time resolution of 52 fs [11].

Once the number of events, background, time resolution, tagging efficiency and mistag fraction were determined, a mini-Monte Carlo was used to generate the expected proper time distributions for a particular value of x_s. Fig. 4(a) and (b) shows the mixed and unmixed time distributions for the $D_s\pi$ mode generated with x_s=40. Fig. 4(c) shows the negative log likelihood function computed from these events. It can be seen that the fit picks out the correct solution at x_s=40. The mini-Monte Carlo also shows how the limiting x_s sensitivity of the experiment is approached. As the number of events is reduced, the negative log likelihood function becomes more and more ragged and the depth of the secondary minima approach that of the true minimum. We define a significant observation as one in which the deepest minimum is deeper than the next deepest by at least 5σ. This is shown by the dashed line. When a solution is found the error is ≈ 0.1. Fig. 5 shows the number of years needed to obtain a significant measurement as a function of x_s. This figure also shows the improvement in x_s reach obtained with the square hole pixel layout.

4.3 CP Violation in $B^0 \to \pi^+\pi^-$

Measurement of the CP asymmetry in the decay $B^0 \to \pi^+\pi^-$ leads to information about the angle α of the unitarity triangle. This decay mode is also an example of a low multiplicity final state which provides a critical test of the Level I trigger algorithm. The large combinatoric background expected for this mode can be reduced by requiring that the secondary vertex be well separated from the primary and that the reconstructed B^0 point back to the primary vertex. Another large source of background comes from other 2-prong B decays - $B_d \to K^+\pi^-$, $B_s \to K^+K^-$, and $B_d \to K^+\pi^-$. This background can be reduced below the level of combinatoric background with good kaon identification in the RICH. Fig. 6(a) shows the contribution to the two pion mass plot from each of these decay modes. Fig. 6(b) shows the signal compared to the sum of all two body modes.

Simulations result in a combined geometric acceptance and reconstruction efficiency of 9.0% and a trigger efficiency for accepted events of 72% [1]. Assuming a branching ratio of 0.75×10^{-5} then we expect 16,000 triggered and reconstructed events per year before tagging. Background studies of 5×10^6 generic B events lead to an estimate of S/B=0.9. If we assume an effective tagging efficiency $\epsilon D^2 = 10\%$ then the statistical error in the time-integrated CP asymmetry is $\sigma_{A_{CP}} = \pm 0.04$. If only tree level diagrams contribute to this decay then α is related to the asymmetry by

$$A_{CP} = \sin 2\alpha \frac{x_d}{1 + x_d^2},$$

however it is expected that contributions from penguin diagrams will not be negligible and other decay modes will need to be studied to determine the penguin effect.

4.4 Measurement of γ

The angle γ of the unitarity triangle is the most difficult to measure experimentally and all methods result in discrete ambiguities. Using several different methods will help resolve these ambiguities. We have studied three methods of measuring γ. The first method uses the decays $B_s \to D_s^{\pm} K^{\mp}$ where a time-dependent CP violation can result from the interference between the direct decay and the mixing induced decay [13]. Consider the following time-dependent rates :

$$\Gamma(B_s \to f) = |M|^2 e^{-t}\{\cos^2(xt/2) + \rho^2 \sin^2(xt/2) - \rho \sin(\phi + \delta) \sin(xt)\}$$

$$\Gamma(\bar{B}_s \to \bar{f}) = |M|^2 e^{-t}\{\cos^2(xt/2) + \rho^2 \sin^2(xt/2) + \rho \sin(\phi - \delta) \sin(xt)\}$$

$$\Gamma(B_s \to \bar{f}) = |M|^2 e^{-t}\{\rho^2 \cos^2(xt/2) + \sin^2(xt/2) - \rho \sin(\phi - \delta) \sin(xt)\}$$

$$\Gamma(\bar{B}_s \to f) = |M|^2 e^{-t}\{\rho^2 \cos^2(xt/2) + \sin^2(xt/2) + \rho \sin(\phi + \delta) \sin(xt)\},$$

where $M = \langle f|B\rangle$, $\rho = \frac{\langle f|\bar{B}\rangle}{\langle f|B\rangle}$, ϕ is the weak phase between the 2 amplitudes and δ is the strong phase between the 2 amplitudes. The three parameters ρ, $\sin(\phi + \delta), \sin(\phi - \delta)$ can be extracted from a time-dependent study if $\rho = O(1)$.

In the case of B_s decays where $f = D_s^+ K^-$ and $\bar{f} = D_s^- K^+$, the weak phase is γ. The decay mode $B_s \to D_s K$, $D_s \to \phi\pi$, $\phi \to K^+K^-$ was simulated and resulted in a combined geometric acceptance and reconstruction efficiency of 4% with S/B=10 [12]. The trigger efficiency is 70%. Using the branching fractions from Aleksan [13] and assuming a tagging efficiency $\epsilon = 15\%$ we expect 350 tagged events per year. We have a total of 800 events, with S/B= 10, if we also use the K^*K decay mode of the D_s.

Using the measured values of S/B and time resolution, a mistag rate of 25%, and x_s=40, a mini-Monte Carlo was used to generate the expected proper time distributions for various sets of input parameters ρ, $\sin(\gamma + \delta), \sin(\gamma - \delta)$. A maximum likelihood fit was then used to extract fitted values of the parameters. Fig.7 shows the distributions of the parameters for a signal of 1000 events with input values ρ=0.5, $\sin\gamma = 0.5$ and $\cos\delta = 0.7$. Assuming that $\sin\gamma > 0$ then $\sin\gamma$ can be determined up to a two-fold ambiguity, hence γ up to a four-fold ambiguity.

The second method described by Gronau and Rosner [14] and Fleischer and Mannel [15] uses $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$ decays. It is particularly promising as it may complement other methods by excluding some of the region around $\gamma = \pi/2$. We expect to reconstruct 3600 $B^\pm \to K_s\pi^\pm$ with S/B=0.5 and 36000 $B^0/\bar{B}^0 \to K^\pm\pi^\mp$ with S/B=3. Gronau and Rosner estimate a measurement of γ to 10° with 2400 events in each channel [16], however there has been much theoretical discussion about the effects of isospin conservation and rescattering which casts doubt on this method [17][18][19][20].

Another method for extracting γ has been proposed by Atwood, Duneitz and Soni [21]. A large CP asymmetry can result from the interference of the decays $B^- \to K^-D^0, D^0 \to f$ and $B^- \to K^-\bar{D}^0, \bar{D}^0 \to f$, where f is a doubly Cabibbo suppressed decay of the D^0 (for example $f = K^+\pi^-, K\pi\pi$, etc.) Since $B^- \to K^-\bar{D}^0$ is color-suppressed and $B^- \to K^-D^0$ is color-allowed, the overall amplitudes for the two decays are expected to be approximately equal in magnitude. The weak phase difference between them is γ. To observe a CP asymmetry there must also be a non-zero strong phase between the two amplitudes. It is necessary to measure the branching ratio $\mathcal{B}(B^- \to K^-f)$ for at least 2 different states f in order to determine γ up to discrete ambiguities. We have examined the decay modes $B^- \to K^-[K^+\pi^-]$ and $B^- \to K^-[K^+3\pi]$. The combined geometric acceptance and reconstruction efficiency was found to be 4% for the $K\pi$ mode and 3.4% for $K3\pi$ with a signal to background of about 1. The trigger efficiency is approximately 70% for both modes. The expected number of $B^\pm$ events in 10^7 s is 190 in the $K\pi$ mode and 320 in the $K3\pi$ mode. With this number of events we expect to be able to measure γ (up to discrete ambiguities) with a statistical error of about $\pm 20°$ in one year of running at $\mathcal{L} = 5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$. The overall sensitivity depends on the actual values of γ and the strong phases.

Table 1: BTeV Physics Reach

Measurement	Accuracy in 10^7 s $\mathcal{L} = 5 \times 10^{31}$	Accuracy in 10^7 s $\mathcal{L} = 2 \times 10^{32}$, $\mathcal{L}$ leveled
x_s (square hole)	up to 64	up to 80 & beyond
$A_{CP}(B^0 \to \pi^+\pi^-)$	± 0.036	± 0.013
$\sin\gamma$ using $D_s K^-$	$\pm 0.14^\dagger$	$\pm 0.05^\dagger$
γ using $D^0 K^-$	$\pm 20^{\circ\ddagger}$	$\pm 7^{\circ\ddagger}$
$\mathcal{B}(B^- \to K^-\mu^+\mu^-)$	4σ at $\mathcal{B}$ of 1.4×10^{-7}	4σ at $\mathcal{B}$ of 5.4×10^{-8}

†Assumes ρ=0.7, $\cos\delta$=0.7, $\sin\gamma$=0.5, x_s=20

‡For most values of strong phases and γ

5 Conclusions

Hadron collider experiments provide the best environment to obtain the high statistics needed for precision measurents of CP Violation and B_s mixing. The forward detector of BTeV has been designed to fit in the new C0 interaction region at the Tevatron and incorporates a silicon pixel vertex detector, downstream tracking and charged paricle identification. The vertex detector enables Level I vertex triggering and excellent time resolution. The strength of the good time resolution is reflected by the fact that x_s can be measured up to a value of 60 in one year of running at a luminosity of $5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$. Eventually we plan to run with a luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ under luminosity leveled conditions which results in a factor of 8 increase in the number of events per year. A summary of the physics reach is shown in Table 1.

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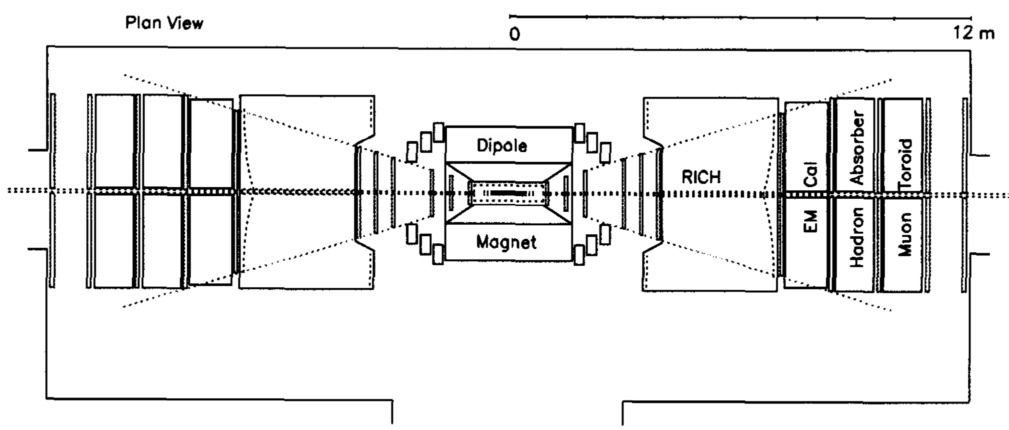

Figure 1: Schematic Layout of the BTeV detector

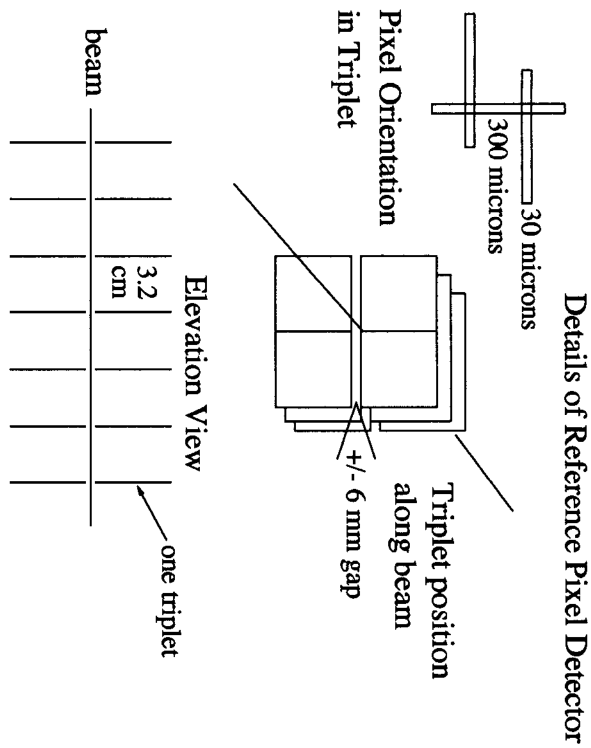

Figure 2: Schematic of the BTeV vertex detector

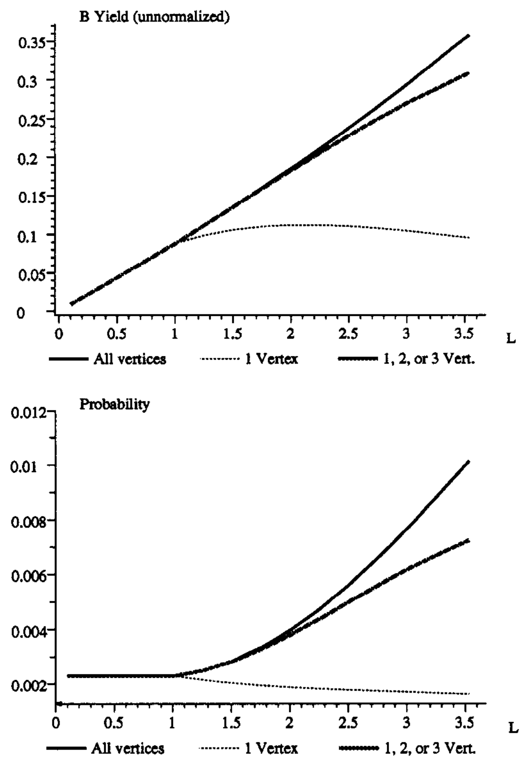

Figure 3: Top curve: The yield for events with $B^o \to \pi^+\pi^-$. Since the curves are not absolutely normalized, their important features are their shapes. Bottom curve: The absolute probability for triggering on crossings with inelastic interactions. For both plots, the lower axis is the luminosity in units of $10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$. The solid line is for events with ≥ 1 reconstructed vertex; the dotted line, for events with one and only one reconstructed vertex; and the thick gray line for events 1, 2, or 3 reconstructed vertices.

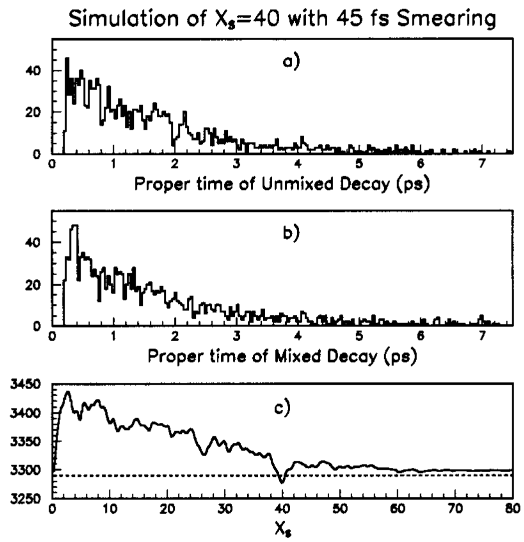

Figure 4: Proper lifetime plots of a) unmixed and b) mixed decays for the decay mode $B_s \rightarrow D_s\pi$ for one year of running. c) the corresponding negative log likelihood as a function of x_s.

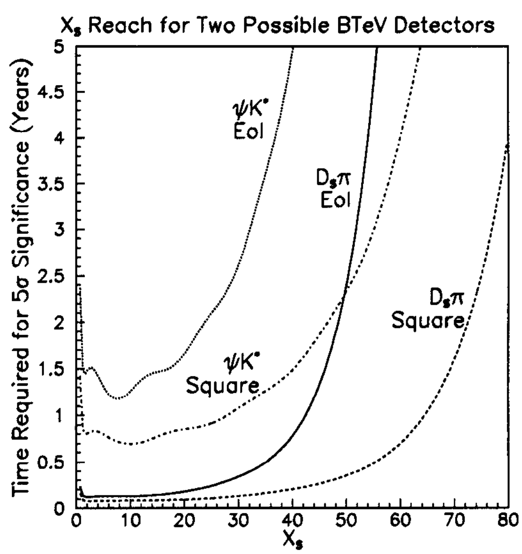

Figure 5: x_s reach of the BTeV detector

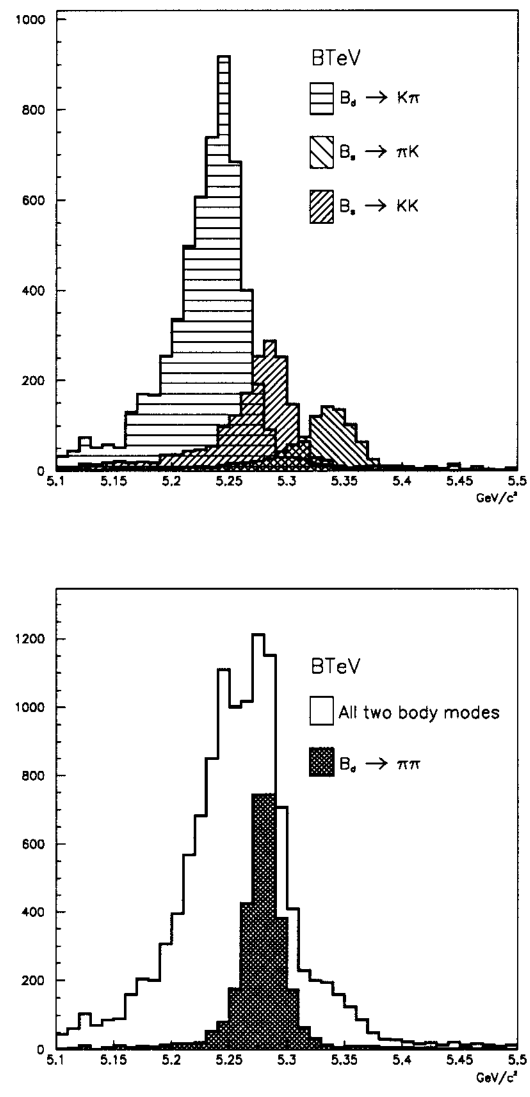

Figure 6: Two body mass plots without particle identification a) including contributions from $B_d \to K^+\pi^-$, $B_s \to \pi^+K^-$, $B_s \to K^+K^-$, b) $B_d \to \pi^+\pi^-$ and a sum of all two body decay modes. All particles are assumed to be pions.

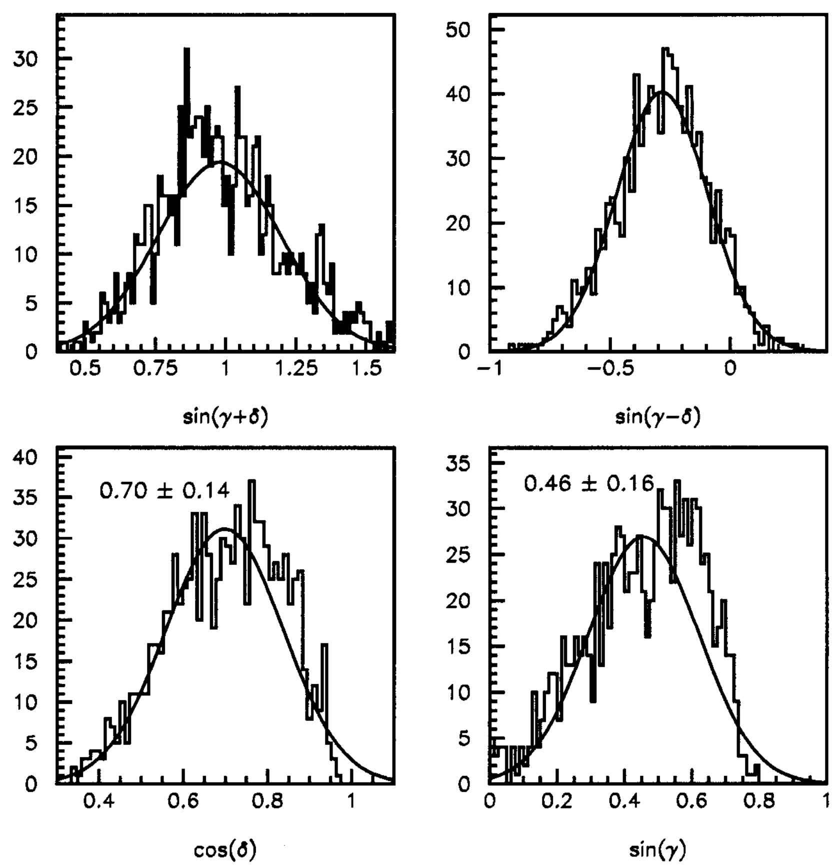

Figure 7: $B_s \to D_s K$, distributions of fitted parameters, for a signal of 1000 events and input values $\sin(\gamma + \delta) = .97$, $\sin(\gamma - \delta) = -.28$, $\sin\gamma = .5$, $\cos\delta = .7$