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Physics Reach of BTeV

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BTeV is a collider program at the Fermilab Tevatron dedicated to the study of CP violation, mixing, and rare decays in beauty and charm hadrons. The detector is a forward spectrometer sited at the C-Zero interaction region.

1. Introduction

BTeV is designed to make precise measurements of Standard Model parameters in the b and c quark systems, and to perform an exhaustive search for physics beyond the Standard Model. The Fermilab Tevatron provides an ideal environment for these studies. At a luminosity of 2×10^{32} cm^{-2} sec^{-1} it will yield 2×10^{11} $b\bar{b}$ per year which is more than three orders of magnitude higher than the e^+e^- machines. In addition, higher mass states such as B_s, B_c and Λ_b can be studied.

BTeV originally received stage 1 approval for a 2-arm spectrometer in June 2000. However due to funding problems at Fermilab we were asked to present a proposal for a descoped detector. In May 2002 the experiment received Stage 1 approval for a 1-arm spectrometer.

The spectrometer is shown in Fig 1. It includes a silicon pixel vertex detector in a dipole field, downstream tracking chambers, a Ring Imaging Cerenkov Counter (RICH), a lead-tungstate electromagnetic calorimeter and muon chambers. The RICH includes both gas and liquid radiators to cover the momentum range 3-70 GeV/c.

Using only data from the pixel detector, the Level 1 vertex trigger reconstructs tracks and vertices in every beam crossing and accepts events which have detached tracks which could signify a b or c decay. The Level 1 trigger has been fully simulated and the efficiencies are above 50% for most b decay modes of interest, while only 1% of minimum bias events are accepted. Simulations show that this trigger is very robust with respect to changes in noise, number of interactions per crossing and pixel resolution.

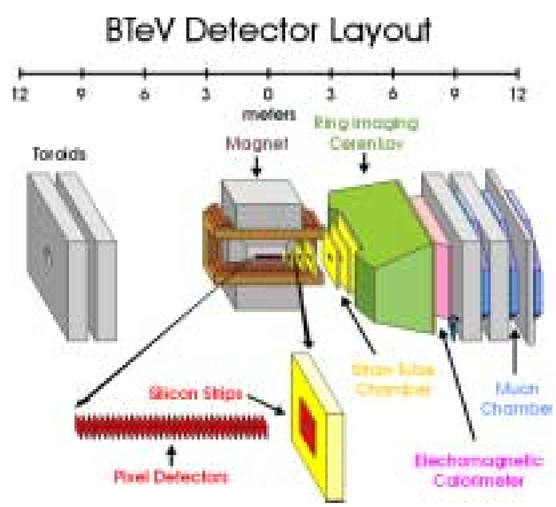

Figure 1. BTeV 1-arm Spectrometer

2. Physics Goals

In the Standard Model CP violation arises from quark mixing with complex terms in the CKM matrix. The standard unitarity triangle comes from the orthogonality of the b and d columns and defines the CKM phases α, β and γ. Anther independent angle is

$$\chi = arg \frac{V^*_{cs} V_{cb}}{V^*_{ts} V_{tb}}$$

which is expected to be ~ 0.02.

BTeV aims to make precise measurements of the CKM phases, to measure CP asymmetries in all flavors of B meson decay, to measure the mass and width difference in B_s mixing, to measure rare B decay rates, and to measure CP violation and rare decays in the charm sector. Physics beyond the Standard Model will be explored by searching for inconsistencies in the Standard Model parameters and for decays that are forbidden in the Standard Model.

3. Physics Reach

Simulations have been done using GEANT3 for both signal and background in a wide range of decays of interest in order to estimate signal to background ratios, efficiencies and resolutions. These numbers are then used in mini-Monte Carlo simulations to estimate errors on parameters to be measured. Since the original BTeV proposal the aerogel radiator in the RICH as been replaced by a liquid radiator which gives better kaon/proton separation at low momentum which in turn leads to higher same-side tagging efficiency for B_s. We now use the RICH to identify leptons outside the geometric acceptance of the ECAL and Muon chambers.

3.1. Removing Ambiguities in β

Although BaBar and Belle now have measured $\sin(2\beta)$, BTeV should be able to improve the measurement with an error on $\sin(2\beta)$ of ± 0.017 for one year of running. A measurement of $\sin(2\beta)$ still leaves a 4-fold ambiguity in β. This can be partially resolved by measuring the sign of $\cos(2\beta)$. One way of doing this is to measure the decays $B \rightarrow \psi K \rightarrow \psi(\pi l \nu)$ where mixing of the B^0 followed by mixing of the K^0 gives terms proportional to $\cos(2\beta)$. If background rates are not too large it will only take on the order of a hundred events to successfully determine the sign of $\cos(2\beta)$. BTeV expects to reconstruct about 1700 events per year in this mode.

3.2. Measurement of γ

There are several ways to measure the angle γ. The decay $B_s \rightarrow D_s K$ gives a model independent determination of γ. CP violation in $B_s \rightarrow D_s K$ arises from the interference between direct and mixing-induced decays. The two amplitudes are expected to be of similar magnitude, and the weak phase between them is γ. The four decay rates $B_s \rightarrow D_s^+ K^-$, $B_s \rightarrow D_s^- K^+$, $\bar{B}_s \rightarrow D_s^- K^+$ and $\bar{B}_s \rightarrow D_s^+ K^-$ depend on x_s, $\Delta\Gamma_s$, the ratio of the two amplitudes, γ and a strong phase δ. If $\Delta\Gamma_s/\Gamma_s$ is small, we can extract $\sin(\gamma + \delta)$ and $\sin(\gamma - \delta)$ from a time dependent fit to the four decay rates, leading to an 8-fold ambiguity in γ. Theoretically $\Delta\Gamma_s/\Gamma_s$ is expected to be ~ 0.16, and in this case we can also measure $\cos(\gamma \pm \delta)$ and resolve all but one ambiguity.

In order to make this measurement we need to have high tagging efficiency, good time resolution and large signal/background. The excellent resolution of the pixel vertex detector enables us to achieve a proper time resolution of 43 fs. The largest source of background is $B_s \rightarrow D_s \pi$ which can be rejected by the excellent particle identification provided by the RICH. We estimate that we will reconstruct about 7500 untagged events per year at full luminosity, which will enable us to measure γ with an accuracy of about 8^o.

3.3. Measurement of α with $B^0 \rightarrow \rho\pi$

The phase difference between the tree amplitudes of the direct and mixed decays in $B^0 \rightarrow \rho\pi$ is α, however large penguin amplitudes prevent the direct measurement of α from the CP asymmetry alone. The three decay modes $B^0 \rightarrow \rho^+\pi^-$, $B^0 \rightarrow \rho^-\pi^+$ and $B^0 \rightarrow \rho^0\pi^0$ all lead to the $\pi^+\pi^-\pi^0$ final state. Snyder and Quinn[1] have shown that a fit to the $\pi^+\pi^-\pi^0$ Dalitz plot can be used to extract the contributions from tree and penguin amplitudes and provide a measurement of α.

In BTeV these events can be separated from background using the precise position resolution of the pixel detector to get a clean two prong secondary vertex, and the excellent resolution (both in energy and position) of the $PbWO_4$ crystal calorimeter for π^0 reconstruction. We estimate that we will reconstruct over 5400 $\rho^\pm\pi^\mp$ and 800 $\rho^0\pi^0$ events per year with signal to background levels of 4:1 and 1:3 respectively. We have performed a Dalitz plot analysis that includes detector resolution and background along with the expected levels of reconstructed signal events and estimate we can make an unambiguous measurement of α with an error of between 1.8^o and 6.1^o, depeding on the value of α.

3.4. Measurement of χ

The CP violating angle χ, defined above, can be measured by using B_s decay modes. The all-charged mode $B_s \to J/\psi\phi$ is one way to measure this, but due to the fact that this is a vector-vector final state of mixed-CP, a complicated angular analysis is required and therefore a very large data sample must be obtained. The channels $B_s \to J/\psi\,\eta'$ and $B_s \to J/\psi\,\eta$, can be used to determine the angle χ from a simple asymmetry measurement. The branching ratios are estimated using a comparison with $B^0 \to J/\psi K^0$. We consider only the decays $\eta \to \gamma\gamma$, $\eta' \to \rho^o\gamma$ and $\eta' \to \pi^+\pi^-\eta$. We expect to reconstruct 2800 events per year in the $B_s \to J/\psi\,\eta$ mode and 9800 events per year in the $B_s \to J/\psi\,\eta'$ mode. This should enable us to measure $\sin(2\chi)$ to an accuracy of 0.024. The accuracy on χ is not precise enough to measure the Standard Model predicted value, which is comparable to the error, in one year of running, however we will run for many years, and we can expect some improvement from the use of $B_s \to J/\psi\phi$.

3.5. x_s Reach

The mode for which BTeV has the most sensitivity to x_s is $B_s \to D_s^-\pi^+$, where the D_s^- decays either by $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$, or by $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$. Both of these D_s^- modes have narrow intermediate states and characteristic angular distributions which can be used to improve the signal-to-background ratio. In one year it is expected that 59,000 events will trigger, survive all analysis cuts and have their birth flavor tagged.

A mini-Monte Carlo was used to study the x_s reach of BTeV. This Monte Carlo generates two lifetime distributions, one for mixed events and one for unmixed events, smears the distributions and then extracts a measured value of x_s from a simultaneous fit of the two distributions. The time smearing is a Gaussian of fixed width, using the mean time resolutions determined above. The model includes the effects of mistagging, background under the signal, and the minimum time cut which is implied by a vertex separation requirement. It is assumed that the lifetime distribution of the background is an exponential with the same mean lifetime as that of the B_s.

Figures 2 a) and b) show the proper time distributions which result from one run of the mini-Monte Carlo for a generated value of $x_s = 40$. The simulation is for the decay mode $B_s \to D_s^-\pi^+$ for one month of BTeV running. Figure 2a) shows the proper time distribution for unmixed decays while Figure 2b) shows the distribution for mixed decays. Figure 2c) of the figure shows, as a function of x_s, the value of the unbinned negative log likelihood function computed from the simulated events. A clear minimum near the generated value of x_s is observed and the likelihood function determines the fitted value to be $x_s = 39.96 \pm 0.08$. A step of 0.5 in the negative log likelihood function determines the 1 σ error bounds and a line is drawn across the figure at the level of the 5 σ error bound.

3.6. Physics beyond the Standard Model

We can look for New Physics either in the context of specific models or more generically, for deviations from the Standard Model expectation.

Decays that occur in the Standard Model only through loops are particularly sensitive to new physics. One example is to examine the rare decays $B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ for branching ratios and polarizations. According to Greub et al. [2], "Especially the decay into K^* yields a wealth of new information on the form of the new interactions since the Dalitz plot is sensitive to subtle interference effects." We expect to reconstruct 2500 events per year in the $B \to K^*\ell^+\ell^-$ mode and 1500 events per year in the $B \to K\ell^+\ell^-$ mode.

In the Standard Model the CP asymmetries in the decays $B^o \to J/\psi K_s$ and $B^o \to \phi K_s$ are expected to be equal. We expect to reconstruct 1150 untagged events per year in the $B^o \to \phi K_s$ mode giving an error on $\sin(2\beta)$ of about 0.2.

Table 1
Summary of Physics Reach of BTeV in 10^7 sec

Decay Mode	$BR(\times 10^{-6})$	# Events	S/B	Parameter	Error (or Value)
$B^0 \to \pi^+\pi^-$	4.5	14,600	3	asymmetry	0.030
$B_s \to D_s K$	300	7500	7	γ	8^o
$B^0 \to J/\psi K_s, J/\psi \to l^+l^-$	445	168,000	10	$\sin(2\beta)$	0.017
$B_s \to D_s\pi^-$	3000	59,000	3	x_s	(75)
$B^- \to D^0(K^+\pi^-)K^-$	0.17	170	1	γ	13^o
$B^- \to D^0(K^+K^-)K^-$	1.1	1000	10		
$B^- \to K_s\pi^-$	12.1	4600	1		$< 4^o$
$B^- \to K^-\pi^0$	18.8	62000	20	γ	+ theory errors
$B^0 \to \rho^+\pi^-$	28	5400	4		
$B^0 \to \rho^0\pi^0$	5	780	0.3	α	$\sim 4^o$
$B_s \to J/\psi\eta$	330	2800	15		
$B_s \to J/\psi\eta^{'}$	670	9800	30	$\sin(2\chi)$	0.024

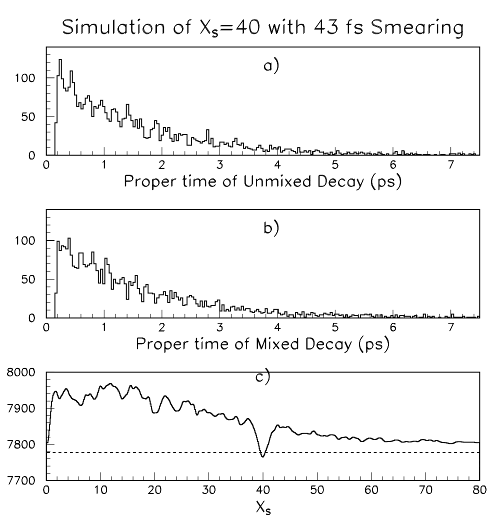

Figure 2. Mini-Monte Carlo proper lifetime plots of a) unmixed and b) mixed decays for a generated value of $x_s = 40$. Part c) shows the negative log likelihood function which was obtained from the entries in parts a) and b).

4. Summary and Conclusions

BTeV will have outstanding performance in in measuring CP asymmetries and excellent potential to discover physics beyond the Standard Model. The physics reach in some of the important decay modes is shown in Table 1. More information about BTeV can be found on its web site[3].

REFERENCES

1. A. E. Snyder and H. R. Quinn, *Phys. Rev. D.* **48**, 2139 (1993).
2. F. J. Greub, A. Ioannissian and D. Wyler, *Phys. Lett.* B **346**, 149 (1995) (hep-ph/9408382).
3. http://www-btev.fnal.gov/