BTeV: Status, Overview and Prospects

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Abstract

The BTeV Collaboration is designing a detector to perform a broad program of studies in flavor physics in the beauty and charm systems: CP violation, flavor mixing and searches for rare and forbidden decays. The program will be sensitive to many signatures for physics beyond the Standard Model. The BTeV detector will be located at the CZero interaction region of the Tevatron p-$\bar{p}$ collider at Fermilab. This report will present the status of the program, review the detector design with emphasis on new developments, survey the projected physics reach, and conclude with expectations for the future.

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The BTeV experiment is designed to make comprehensive and precise studies of CP violation, flavor mixing and rare decays in the beauty and charm systems. These studies represent a small but important piece in the larger puzzle of flavor physics, a subject with many open questions. Why are there families of quarks and leptons? Why three? Can the values of quark mixing angles be explained? Why is there a mass hierarchy? Is it in any way related to the hierarchy in the mixing angles? Is CPT violated? If so, what physics is behind it? What is behind the matter/anti-matter asymmetry in the universe? What are the similarities and differences in the mass hierarchies and mixing angles in the quark and lepton sectors? These questions, and many related ones, will be addressed by the coming generations of b and c experiments, along with their kaon, neutrino and cosmological counterparts.

In January 1999, BTeV received its first formal recognition when when the Fermilab Directorate approved a Research and Development (R&D) program with a goal of achieving a feasible and affordable design for the detector. The following spring the collaboration submitted to the lab a proposal[1] to build a two arm spectrometer. After an extensive internal review, the Fermilab Directorate gave Stage I approval to this proposal, which represents their judgment that the physics is interesting, timely, achievable and affordable. By the fall of 2001 the funding situation for the US HEP program had deteriorated and Fermilab management asked BTeV to submit a descoped proposal. They also stated that BTeV should plan to reuse IR components from either CDF or D0, after the conclusion of their physics programs. The descoped design was required to fit into a draft funding profile, in which construction funds would be available between 2004 and 2008.

In response to this request, the collaboration prepared a Proposal Update[1], in which costs were reduced by staging the construction so that, initially, only one arm will be installed. This leaves open the possibility of a second arm in the event of improved funding at a later date. Because both b hadrons from a forward $b\bar{b}$ event almost always go into the same arm of the spectrometer, the loss of one arm costs a simple factor of two in acceptance, not more. Costs were also reduced by reusing some of BTeV's extensive online computing resources for offline analysis and by making maximal use of computing facilities at collaborating universities. This reduced the cost estimate by about M\$70., to about M\$110. When it was reviewed by the Fermilab Physics Advisory Committee (PAC), the proposal update was unanimously approved. Moreover they recommended that, as the funding situation evolves, lab management explore other plans to build a dedicated IR for BTeV. Based on the PAC recommendations, the Fermilab directorate reaffirmed Stage I approval for BTeV.

The newly re-approved, descoped BTeV apparatus is shown in Figure 1. At the heart of BTeV, surrounding the IR is a high precision vertex detector made from 30 stations of silicon pixel detectors. Each pixel is $50 \times 400\,\mu\mathrm{m}^2$ and each station provides two views, a precision x view and a precision y view. The choice of pixels, rather than silicon microstrip detectors, was dictated by the extremely low occupancy required by the algorithm chosen for the main trigger: the pixel data for each beam crossing is sent to a pipelined Level 1 trigger which does track and vertex finding in real time. The trigger decision is based on evidence for tracks and vertices that are detached from the main vertex. This is a very general signature for heavy flavors, sensitive to a wide variety of decay modes, not just to those whose impor-

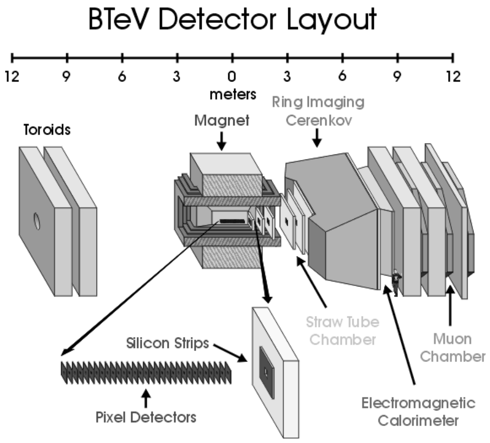

Figure 1: The BTeV Detector, showing the layout of the major elements.

tance is already appreciated. Such an open trigger strategy makes BTeV a truly general purpose b and c detector.

In the descoped design, BTeV retains the full pixel detector in order to retain full coverage of the IR and to make use of away side tracks in finding the primary vertex, both by the Level 1 trigger and offline.

The pixel detector is surrounded by an analyzing dipole magnet, with a field strength of about 1.6 T. Because the pixel detector is within the magnetic field, momentum information is available to the detached vertex trigger, which allows the trigger to suppress false triggers from low momentum tracks with large multiple scattering.

Downstream of the pixel detector are the first six stations of the forward tracking system. Each station is built using silicon strip detectors close to the beamline, where occupancies are high, and straw tubes farther from the beam line. This system contributes to the excellent momentum resolution and it provides precise measurements of the track positions at the entrance to a Ring Imaging Cherenkov (RICH) detector.

Immediately downstream of the sixth tracking station is the RICH detector. In order to provide excellent e-μ-K-π-p separation over the momentum range $3. < p < 70.$ GeV/c^2, the RICH contains two radiators, gaseous C_4F_{10} throughout the main body of the detector and a thin layer of liquid C_5F_{12} at the front face. As described in [2], this represents a change from the original BTeV design in which the thin front radiator was made from aerogel. In order to detect Cherenkov rings from the C_5F_{12}, the sides of the gas box are now instrumented with photo-multiplier tubes.

The BTeV RICH detector has significant lepton identification (ID) power, particularly at large polar angles and low momentum, a kinematic region which is important for b physics but which is not covered by the ECal and muon systems. When the RICH is included in the lepton ID algorithms, the efficiency increases by a factor of $\approx$2.4 for channels which require one identified lepton and by a factor of $\approx$3.9 for channels which require two identified leptons.

Downstream of the RICH detector is the seventh, and final, forward tracking station, followed by the electromagnetic calorimeter (ECal). This tracking station provides a precision measurement of track positions at the RICH mirror and at the impact point of the track on the ECal. The BTeV ECal is made from 10500 crystals of $PbWO_4$, chosen for their unique combination of light output and radiation hardness, arranged in a projective geometry. This is one of the first crystal calorimeters to be designed into a detector at a hadron collider and, as discussed in [2], it promises B-factory-like performance for the efficiency with which it can reconstruct single photons and for the mass resolution which it can achieve on B meson decays to states with one π°.

Downstream from the ECal is a muon detector, made up of three tracking stations, two magnetized steel hadron absorbers and an iron shield. The field in the magnetized steel is toroidal and enables momentum measurement in a stand alone dimuon trigger. This trigger can be used to calibrate the detached vertex trigger and also to augment the trigger efficiencies for important channels containing two muons.

Together, the RICH, ECal and muon system form a powerful and efficient charged particle ID system, one of the great strengths of BTeV. For most decay modes of interest, the final state particles can be well identified over most of their kinematic range. Particle ID is important, both for the reduction of combinatoric background in signal channels and for flavor tagging. Therefore, in most studies, the particle ID ability enters with a high power. BTeV expects to achieve a flavor tagging power, ϵD^2, of 0.10 for B_d mesons and 0.13 for B_s mesons [2].

The BTeV detector will be read out using a high bandwidth trigger and DAQ system. During the descoping to one arm, the full bandwidth was retained in order to provide operational headroom. The main Level 1 trigger considers every beam crossing and, using only the pixel information, looks for evidence of a detached vertex. It is designed to reject 99 of 100 minimum bias events and, depending on decay mode, has an efficiency of >50% for signal events that pass all analysis cuts. Further details of this trigger can be found in [3]. The full Level 1 trigger is an OR of the detached vertex trigger and a stand alone muon trigger.

The Level 2 and 3 triggers will be implemented using a large farm of general purpose processors, several thousand nodes in all. This farm is sized to deal with the peak trigger rate at the start of a fill and one of the unique features of BTeV is a plan to use the spare cycles on this farm, late in a fill and during down times, to perform offline analysis [4]. The Level 2 algorithm will refine the tracking and vertexing, again using only the pixel information, and will look for higher quality evidence of a detached vertex. It is designed to have background rejection of about 10:1 and a signal efficiency of about 90%. The Level 3 algorithm, which is still under development, will use information from all detector components and must provide a background rejection of about 2:1 for a signal efficiency of about 90%; it will look for both general evidence of heavy flavor and for specific decays of interest. This system is capable of writing about 4,000 Hz of b and c events, totaling about 2 PB of raw data each year.

This next section will highlight selected topics in the BTeV physics program, the full details of which, along with an extensive bibliography, are available in the BTeV proposal and related documents[1]. Additional information is available in the report of the workshop on B Physics at the Tevatron [5].

Although the CKM angle β is already measured, it is expected that improved precision

Reaction	B×10^{-6}	# Events/Year	S/B	Parameter	Sensitivity
$B^\circ \to \pi^+\pi^-$	4.5	14,600	3	Asymmetry	± 0.03
$B_s \to D_s^\pm K^\mp$	300	7,500	7	γ	8°
$B^\circ \to J/\psi K_S^\circ$	445	168,000	10	$\sin(2\beta)$	± 0.017
$B_s \to D_s^\pm \pi^\mp$	3000	59,000	3	x_s	> 75
$B^- \to D^\circ(K^+\pi^-)K^-$	0.17	170	1	γ	
$B^- \to D^\circ(K^+K^-)K^-$	1.1	1,000	> 10	γ	13°
$B^- \to K_S^\circ \pi^-$	12.1	4,600	1		
$B^- \to K^+\pi^-$	18.8	62,100	20	γ	$< 4^{\circ\ddagger}$
$B^\circ \to \rho^+\pi^-$	28	5,400	4.1		
$B^\circ \to \rho^0\pi^0$	5	780	0.3	α	$\approx 4^\circ$
$B_s \to J/\psi\eta$	330	2,800	15		
$B_s \to J/\psi\eta'$	670	9,800	30	χ	± 0.024

Table 1: The sensitivity of BTeV to selected observables. With one exception, the sensitivities are quoted for one year of running at the nominal Tevatron conditions, $E_{\rm CM} = 2$ TeV and an integrated luminosity of 2 fb^{-1} per year. The sensitivity to α using $B \to \rho\pi$ is quoted for 1.4 years of running.

will still be important in the BTeV era. A summary of the sensitivity to this and other Standard Model (SM) CKM parameters is given in Table 1.

BTeV is also sensitive to a broad range of signatures for physics beyond the SM. This includes both the ability to make specific tests, suggested by particular models, and the ability to check for SM consistency without reference to any particular model. In the decays $B \to K^{(*)}\mu^+\mu^-$, for example, the SM makes a specific prediction for the dependence of the $\mu^+\mu^-$ forward-backward asymmetry on the invariant mass of the $\mu^+\mu^-$ system. Any deviation from this prediction indicates some sort of new physics. A second example is a test [6] using the CKM angle χ, which checks the Standard Model in a more profound way than simple checks for the closure of unitarity triangles. The precision of this test will be limited by the sensitivity to χ, which, in one year, BTeV can measure using $B_s \to J/\psi\ \eta^{(\prime)}$ to ± 0.024.. The $PbWO_4$ ECal makes BTeV particularly well suited to make this measurement.

On the other hand, new physics may be discovered at one of the energy frontier machines. Wherever, and however, new physics may be discovered, a broad program of measurements will be required to distinguish among the candidate scenarios. Many differences can be best distinguished by looking for for effects of the new particles in loop diagrams which mediate rare b and c decay processes. BTeV will be ready and able to contribute to this program.

BTeV will operate at the same time as LHC-b, which has 5 times the $b\bar{b}$ cross-section. However BTeV has a much more open trigger strategy, which allows 5 times as many b events to be accepted per second. For most channels this will more than offset the cross-section advantage. Moreover BTeV has a crystal ECal, which will give it an advantage in final states containing neutrals, such as those required to measure χ. Recently e^+e^- Super B-factories have been proposed. In order for such machines to compete with BTeV in B_d and B_u physics, they would require a luminosity of 10^{36} cm^{-2} s^{-1} and in no case would they compete in B_s,

B_c or b-baryon physics. For a 10^{36} machine, there are serious technical obstacles for both the storage ring and the detector. Moreover the recent HEPAP subpanel report [7] suggests that the cost of one such machine would be of order M$500, a few times the cost of BTeV.

What is next for BTeV? Since this conference Fermilab has conducted a internal review, modeled on the Lehman review process, of the cost, schedule and risk of the detector. BTeV passed that review and is preparing for a P5 review by the Department of Energy; the precise timing and terms of this review are still being formulated. Presuming all goes well, a baseline cost and schedule review will follow some months later. The hope is to have this process complete by the start of fiscal year 2004.

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