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The BTeV experiment

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Abstract. BTeV is an approved forward collider experiment at the Fermilab Tevatron dedicated to precision studies of CP violation, mixing, and rare decays of beauty and charmed hadrons. The BTeV detector has been designed to achieve these goals. Pixel detectors cover the interaction region and vertex computation is included in the lowest level trigger.

1 Introduction

The BTeV experiment [1] is an approved forward collider experiment at the Fermilab Tevatron dedicated to B physics. The experiment will begin data taking in 2009.

Measurements by DØ have shown that at the Tevatron the $b\overline{b}$ cross section is at least 100 μb [2]; the $c\overline{c}$ cross section is expected to be an order of magnitude higher. Much of this production is in the forward direction. Furthermore, as shown in Fig. 1, when the b hadron is in the forward direction, the $\overline{b}$ hadron is also likely to be in the forward direction. This is especially important for mixing and CP analyses where flavor tagging is crucial.

The fraction of interactions which produce $B\bar{B}$ pairs is approximately 0.2%; BTeV is expected to have a B triggering efficiency of $> 50\%$. Running at an average luminosity of 2×10^{32} cm^{-2}s^{-1}, BTeV will reconstruct about 2×10^{11} $B\bar{B}$ pairs/year.

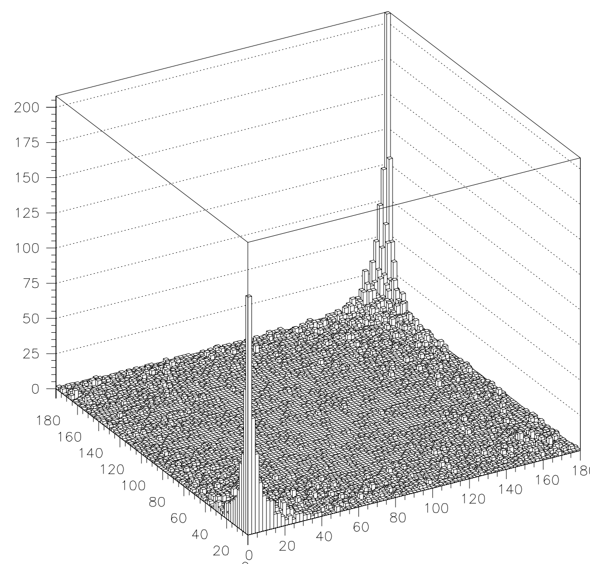

Fig. 1. Production angles for B and $\bar{B}$ a the Tevatron. Large numbers of correlated $B\bar{B}$ pairs are produced at 0° and 180°

2 B physics at hadron colliders

Despite (and in addition to) these high rates of B production, B physics at a hadron collider presents additional opportunities and challenges when compared to e^+e^- collider experiments.

One of the primary advantages provided by hadron colliders is the production of all species of b hadrons, not just B^0 and B^+. This is important, because to test the consistency of the Standard Model description of CP violation, one must also study CP violation in the B_s^0 sector. The B_s^0 analogue to β in B^0 mixing, χ, is expected to be small (a few degrees). Additionally, not much information is known about the B_c^+, Λ_b^0, Ξ_b, and Ω_b states. Results from hadron machines will be crucial in understanding the b baryons.

Another advantage of the forward hadron collider environment is that relativistic boosts of the particles are large, making it comparatively easy to measure particle lifetimes with great accuracy. This is especially useful in mixing measurements; while $\Delta\Gamma$ in B_s^0 mixing may be measured at CDF and DØ, mixing angle measurements of the B_s^0 require this precise lifetime measurement capability.

B physics in a hadron environment is also challenging. The lack of 4π coverage removes the ability to use beam constraints. Additionally, the larger fraction of background events and the larger multiplicities makes electromagnetic calorimetry and particle ID more challenging. Moving the study of CP violation beyond $\sin 2\beta$ to redundant measurements of the other CP violating angles α, β, γ, and χ requires effective photon detection.

B factories at hadron colliders are well positioned to make these crucial measurements.

3 The BTeV spectrometer

Because it instruments the forward region (10–300 mrad), the BTeV spectrometer resembles past fixed target experiments in overall layout. Fig. 2 shows a schematic overview of the BTeV spectrometer. $p\overline{p}$ interactions occur at the center of a large dipole magnet. These interactions are traced, within the magnetic field, by a silicon pixel detector. "Downstream" tracking is performed with silicon trackers in the most forward regions and straw tube trackers in the lower occupancy regions. A Ring Imaging Čerenkov (RICH) is used for charged particle identification, electrons and photons are reconstructed in a lead tungstate ($PbWO_4$) crystal calorimeter, and muon identification is performed with muon detectors shielded by magnetized steel toroids.

Pixel Detector: The pixel detector sits inside a 1.6 T magnetic field. By providing accurate 3-D space points, it makes the challenging vertex trigger (described later) possible as well as providing accurate vertexing information for physics reconstruction. The detector consists of 30 stations of doublets along the beam direction with a pixel size of 50×400 μm. There are approximately 23 million channels in the full detector.

Tracking Detectors: Additional tracking in BTeV is provided by seven stations of tracking chambers, each of which consists of silicon strip detectors in the forward region and straw detectors in the outer region. Three of these stations are located within the magnetic field, the rest are outside it. The silicon detectors have a pitch of 100 μm and cover the central 27×27 cm^2 at each station. The straws have a diameter of 4 mm and are arranged in 3 views, each of which has three layers arranged in a close packed geometry.

RICH Detector: For charged particle identification, BTeV will use a RICH detector. In order to obtain good separation between particle species over a range of momentum, two radiators will be used: a liquid radiator (a thin layer of C_5F_{12} at the front of the detector) and a large gas radiator volume of C_4F_{10}. Photons from the gas radiator will be reflected and detected on 163-channel Hybrid Photodiodes (HPD) or 64-channel Multi-Anode Photomultiplier Tubes (MAPMT) while photons from the liquid radiator will be directly detected with 3" PMTs which, due to the large Čerenkov angles will be mounted on the sides of the detector. The combination of these two radiators will provide good K-π and p-K separation out to 70 GeV/c. Additionally, in the wide angle, low momentum region not covered by the muon detector (as described below) the RICH will be able to provide π-μ separation.

Electromagnetic Calorimeter: Photon and electron reconstruction will use a $PbWO_4$ (lead tungstate) crystal calorimeter. These are the same crystals being used by CMS. Each crystal will be $2.8 \times 2.8 \times 22$ cm^3. Because these crystals are very fragile, each crystal (or at most, small groups of crystals) must be individually supported. Lead tungstate provides excellent energy resolution; in beam tests, BTeV has found an energy resolution of

$$\sigma_E/E = (0.33 + 1.8/\sqrt{E})\% \,.$$

Combined with the small crystal size, this will give BTeV electromagnetic calorimetry similar in performance to detectors at e^+e^- machines.

Muon Detector: Muon identification in BTeV will be provided by a system of proportional counters. There are three stations of muon detectors with four views per station (2 r views, u, and v views). Each view consists of layers of stainless steel tubes (3/8" diameter) arranged in a picket fence geometry. "Upstream" of the first station and between the first and second stations are 1 m thick magnetized steel toroids which absorb other particles and also allow a stand-alone momentum measurement.

The momentum measurement also allows a completely independent J/ψ trigger at the first level to enhance samples of interesting decays and to provide an unbiased selection of events for calibrating the crucial first level vertex trigger.

4 Detached vertex trigger

To collect the maximum number of B decays, BTeV will employ a detached vertex trigger at the first level which will partially reconstruct every event. Every beam crossing is read out by the DAQ and stored in 1 TB of buffer memory. Crossings will occur in the Tevatron with a maximum rate of 7.6 MHz if 132 ns bunch crossings can be achieved (396 ns is the current expectation).

First level triggering will be performed by a cluster of Field Programmable Gate Arrays (FPGA) and about 2500 Digital Signal Processors (DSP) for the vertex trigger and an additional cluster of about 500 DSPs for the di-muon trigger. This ambitious vertex trigger is only possible because of the 3D space points provided by the pixel detector.

The detached vertex trigger algorithm begins with FPGAs assembling vertex hits into track segments. Hits near the interaction region and near the edges of the pixel planes are used. The inner region hits help define intercepts and vertex positions, the outer hits are used to refine the track vectors and to measure the momenta as the particles are bent in the magnet.

These track segments are then passed to the farm of DSPs for segment matching and vertex reconstruction. The DSP-based trigger algorithm looks for a production vertex and tracks that miss that vertex. Our current algorithm requires two tracks that miss the production vertex by $> 6\sigma$. Because a momentum measurement is also performed, we can also put requirements on p_T of the tracks. This will be essential in removing the more copious charm decays, which are largely a background for BTeV.

5 Comparison with LHCb

BTeV's primary competition will come from the LHCb experiment at CERN. Both will begin data taking at about the same time and aim to do much of the same physics, however there are significant differences in the detector designs.

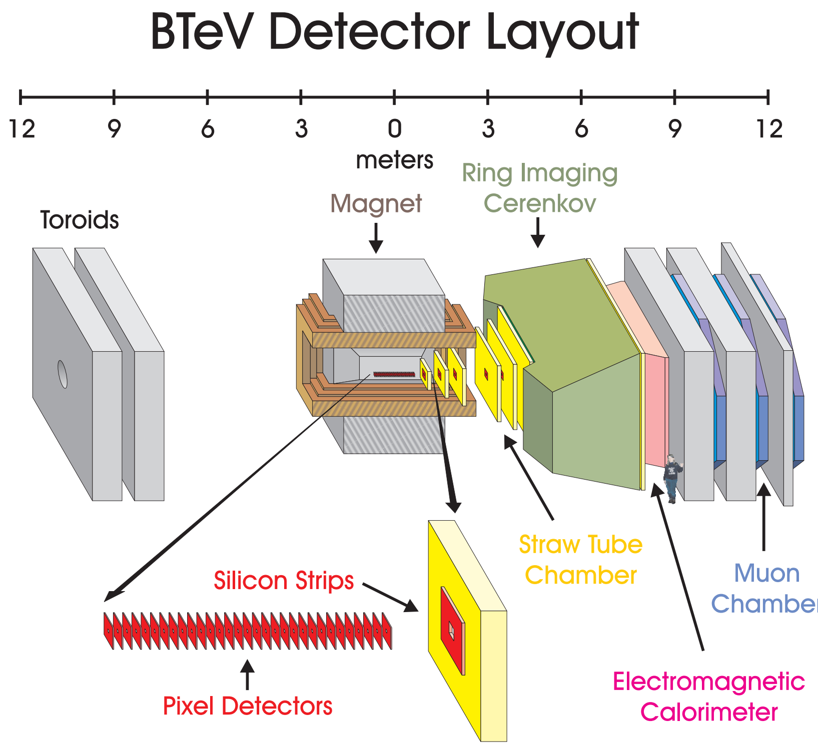

Fig. 2. The BTeV Spectrometer

LHCb has several advantages over BTeV:

- The $b\overline{b}$ cross section at the LHC is expected to be about five times higher than at the Tevatron while the total cross section is only about 1.6 times higher.
- LHCb will operate with less than one interaction per beam crossing, while BTeV will operate with 2–6 depending on the crossing time. However, the crossing time at LHC is 25 ns, somewhat below the response times of most detectors.

BTeV will have a number of advantages over LHCb as well:

- BTeV has a dipole located on the interaction region which gives it a spectrometer covering the forward antiproton rapidity region. This will aid in locating production vertices.
- BTeV uses a precision vertex detector based on planar pixel arrays.
- The pixel detector enables a vertex trigger at Level 1. This makes BTeV especially efficient for states that have only hadrons and allows for less restrictive definitions of "interesting" events.
- The pixel detector also helps minimize confusion for multiple interactions per crossing.
- BTeV has a lead tungstate electromagnetic calorimeter, giving it very good capabilities for photon and π^0 reconstruction.
- BTeV plans a very high capacity data acquisition system which frees it from making excessively restrictive choices at the trigger level. This will give us an unbiased selection of b and c decays and means that as new physics becomes interesting, we will have those events "on tape" already.

6 Conclusions

The frontier in studies in B flavor physics will move to hadron colliders. The BTeV experiment, with its innovative design and triggering, will help make the next decade in B physics as interesting as the current one.

References

1. BTeV web site, `http://www-btev.fnal.gov/`
2. D. Fein: Tevatron results on b-quark cross sections and correlations, 1999, Presented at Hadron Collider Physics (HCP99), Bombay