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BTeV detached vertex trigger

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Abstract

BTeV is a collider experiment that has been approved to run in the Tevatron at Fermilab. The experiment will conduct precision studies of CP violation using a forward-geometry detector. The detector will be optimized for high-rate detection of beauty and charm particles produced in collisions between protons and anti-protons. BTeV will trigger on beauty and charm events by taking advantage of the main difference between these heavy quark events and more typical hadronic events—the presence of detached beauty and charm decay vertices. The first stage of the BTeV trigger will receive data from a pixel vertex detector at a rate of 100 gb s^{-1}, reconstruct tracks and vertices for every beam crossing, reject 99% of beam crossings that do not produce beauty or charm particles, and trigger on beauty events with high efficiency. An overview of the trigger design and its influence on the design of the pixel vertex detector is presented.

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1. Introduction

The BTeV experiment [1] is expected to begin running in the new Tevatron CZero interaction region at Fermilab by the year 2006. The physics goals include studies of CP violation and mixing, rare decays, and high sensitivity searches for decays forbidden within the Standard Model. The main focus of BTeV is on precision studies of CP violation and mixing in B decays.

The vertex trigger is the primary physics trigger for BTeV. The trigger selects B events by detecting the presence of detached beauty or charm decay vertices. It finds these vertices by utilizing the superior pattern recognition capabilities of the BTeV pixel vertex detector to reconstruct tracks and vertices in the first stage of the trigger, Level 1 [2]. Subsequent stages of the trigger improve the track and vertex reconstruction performed at Level 1, and impose more refined selection criteria that include data from other detectors in the BTeV spectrometer.

This paper provides a brief overview of the BTeV spectrometer, with emphasis on the pixel vertex detector. It describes the Level 1 trigger, and how the design of the trigger algorithm is influenced by the physics goals of the experiment and the design of the vertex detector. Furthermore, the design of the vertex detector is influenced by ideas that have emerged from our study of various trigger algorithms. We have learned that the pixel vertex detector and Level 1 trigger should be viewed as a unified system, and that concurrent development of the vertex detector and trigger is essential.

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2. Detector overview

The BTeV detector is a two-arm forward-geometry spectrometer (see Fig. 1) designed to run at a luminosity of 2×10^{32} cm^{-2} s^{-1} and an anticipated B production rate of 4×10^{11} B hadrons per year. This rate of B production is high, but background from light quark events is also large (only 1 in 500 events is expected to be a B event). The Level 1 trigger is designed to reject 99% of background events while maintaining high efficiency for a broad spectrum of B decays (such as decay modes that contain only hadrons in the final state). The trigger selects B decays by reconstructing interaction vertices, where B particles along with many other particles are produced, and by searching for evidence of the decay of a particle within a few hundred microns to a few millimeters away from the interaction vertex. The trigger performs this operation for every beam crossing at a rate of 7.6 MHz. This means that a trigger decision must be made on average every 132 ns.

The two-arm forward-geometry design of the BTeV spectrometer involves significant design challenges. However, the forward geometry provides considerable advantages for B physics compared to a more central detector. The main advantage is a larger Lorentz boost, which increases the reconstruction efficiency for B decays and improves the proper time resolution. Another significant advantage is that a forward detector can incorporate much longer detector volumes, and this is exploited in our design by including large volume Cherenkov counters for particle identification. Furthermore, having a two-arm configuration with a dipole magnet centered on the interaction region means that BTeV consists of two spectrometers, one in the forward proton direction and one in the forward anti-proton direction. This doubles the acceptance for B physics compared to a single-arm spectrometer, but only requires a single central tracking device and trigger.

BTeV includes detectors for charged-particle tracking, particle identification, E&M calorimetry, and muon detection. The particle identification is handled by Ring Imaging Cherenkov (RICH) counters, one in each arm of the spectrometer. The RICH detectors are ideal for charged-hadron identification and are ultimately used to distinguish different types of B decays. The charged-particle tracking consists of *vertex* and *forward* tracking systems. The vertex tracking system is a silicon pixel vertex detector with 30 million pixels for precision tracking and vertex reconstruction. The forward tracking system is used to extend tracks that originate in the pixel detector, to improve the momentum determination for these tracks, and to reconstruct particles that decay outside the pixel detector.

For this paper the silicon pixel vertex detector is of prime importance, since it provides the data for the Level 1 trigger. The pixel detector consists of

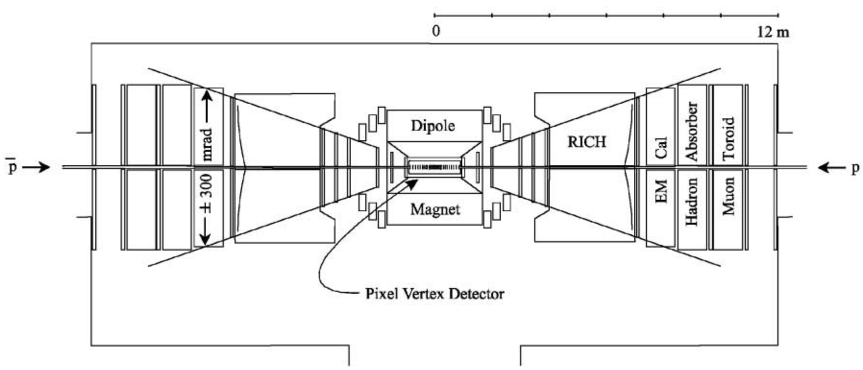

Fig. 1. Plan view of the BTeV detector in the CZero interaction region.

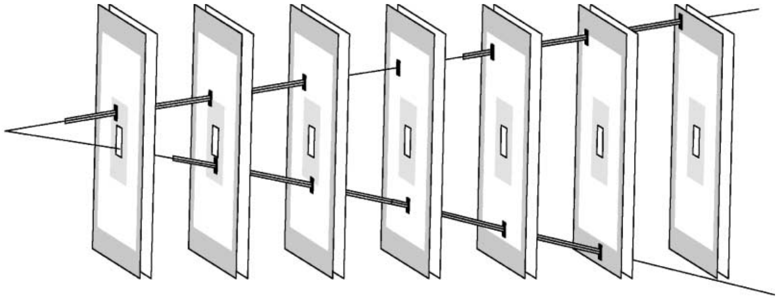

Fig. 2. Pairs of pixel planes with (shaded) "inner" and "outer" regions within which track seeds are sought. In the figure, track seeds for the track near the top of the figure are found in the first and last tracking stations. For the lower track the seeds are found in the second and second-to-last stations.

planar pixel arrays located inside the Tevatron beam vacuum and inside the 1.6 T magnetic field of the spectrometer magnet. In our current design there are 31 pixel tracking *stations* separated by 4.25 cm (center-to-center) and distributed over 128 cm. Each station has two pixel *planes* (see Fig. 2) arranged in two views,[1] a bend view and a non-bend view, with respect to the magnetic field. Each plane has about 500,000 pixels in a 10 cm $\times$ 10 cm area, excluding the *beam region* located at the center of each pixel plane. Each pixel, which is 50 μm $\times$ 400 μm in size, provides an x and y position measurement, and a pulse-height measurement. The pixels are located on sensor chips that are arranged as "shingles" to provide close to 100% coverage over the active area of the vertex detector. The shingles are supported by a movable structure that allows the pixels to be positioned at a safe distance away from the Tevatron beams until stable conditions have been established, at which point they are moved as close to the beams as radiation damage considerations will allow. In our design studies we position the inner edge of each pixel plane 6 mm from the Tevatron beams. This defines the cross-sectional area of the beam region as a square that is 1.2 cm $\times$ 1.2 cm in size.

[1] We define a "view" for a pixel detector plane as being analogous to the orientation of a silicon strip detector. Since the pixels are rectangular in shape, the long dimension of a pixel is analogous to the long dimension of a silicon strip.

3. The Level 1 trigger algorithm

The Level 1 trigger operates at the full 7.6 MHz beam-crossing rate and is the most demanding part of the BTeV trigger system. At this rate and at an anticipated luminosity of 2×10^{32} cm^{-2} s^{-1}, the trigger must cope with an average of two interactions every 132 ns. As mentioned above, the trigger attempts to reconstruct the primary vertex associated with each interaction. It then selects those events that have tracks with large impact parameters (the signature of a B decay) with respect to the nearest primary vertex.

The Level 1 trigger receives data from the silicon pixel vertex detector. The data consist of pixel hits that are grouped into pixel clusters before they are sent to the trigger. Each cluster represents a position measurement that has a spatial resolution better than 10 μm [3]. The operations that are performed on this data by the trigger include the sorting of pixel clusters, pattern recognition to find track segments, track reconstruction and extrapolation to the beam region, vertex reconstruction, impact parameter calculations, and event selection based on the number of tracks with large impact parameters. Tracks with very large impact parameters, greater than 2 mm, with respect to a vertex are ignored so that we can exclude tracks associated with other primary vertices, and strange particle decay daughters. The trigger selects events by requiring that at least n tracks (all directed at one arm of the BTeV spectrometer) miss a primary vertex by at least $m\sigma$. The values for n and m are chosen to achieve the desired background rejection and trigger efficiency for B events.

Operations performed by the trigger can be divided into two groups. The first group consists of sorting the pixel clusters and pattern recognition. These operations involve a small number of mathematical steps, and a large number of pixel clusters and combinations of pixel clusters that must be considered to find tracks. The operations are performed by ≈ 500 field-programmable gate arrays (FPGAs) operating in parallel on the data. The second group consists of all remaining operations. These involve a large number of mathematical steps performed on a modest number of tracks segments found for each beam crossing. These operations are performed by ≈ 2500 digital signal processors (DSPs) that are subdivided into two DSP farms. The DSPs in one farm are used for track reconstruction, while the second farm is used for the remaining operations (e.g. vertex reconstruction). The calculations that are done by these DSPs are not unlike the analyses that are typically performed by offline reconstruction programs in particle-physics experiments. The track reconstruction uses the 3D pixel clusters provided by the pixel detector and the curvature of tracks in the magnetic field to extrapolate tracks to the beam region and calculate track parameters. The track parameters are used to find primary vertices for tracks that appear to come from a common point in the beam region. Details of these calculations are not presented in this paper.

The pattern recognition performed by the Level 1 trigger is described in greater detail in this paper, since it is unique to BTeV. It is the most demanding part of the Level 1 trigger algorithm (in terms of computing power and data-transfer bandwidth), and depends quite significantly on the design of the silicon pixel vertex detector.

The Level 1 trigger performs pattern recognition for pixel clusters that belong to a single beam crossing in parallel for all tracking stations. At first, only the pixel clusters from the bend view are considered. These are the pixels that provide a more precise measurement of the curvature of tracks in the magnetic field. Pixel clusters from the non-bend view are used at a later stage to confirm candidate tracks and to improve the measurement accuracy for track segments.

Since every pixel cluster in a plane could be part of a track, the number of pixel–cluster combinations that may need to be considered for pattern recognition could be quite large. With an average of about 15 clusters/plane for each beam crossing, the number of cluster combinations per tracking station could easily number in the hundreds. We use several strategies to reduce the number of combinations that need to be tested. First, we subdivide the data into quadrants. This limits the pattern recognition to cluster combinations confined to a quadrant, and incurs a track reconstruction inefficiency of a few percent. Second, we restrict the pattern recognition so that we only find track segments at a track's entry point into the pixel detector, where a track projects into the beam region, and at the exit point, where the track projects outside the detector fiducial volume. This means that only those pixel clusters within a region of "inner" pixels (i.e. pixels within a specified distance from the inner edge of each pixel plane) and a region of "outer" pixels (within a specified distance from the outer edge) need to be used as "seeds" for track finding (see Fig. 2). These geometric constraints substantially reduce the number of cluster combinations that must be examined, and the amount of hardware needed for the trigger. Another reason for this strategy is that the pixel clusters at a track's entry point give the best resolution for projection to a vertex, while clusters at the track's exit provide the best momentum resolution for tracks in the vertex detector.

Once the pixel clusters have been selected, the pattern recognition begins. "Inner pixel clusters" are used to find tracks where they enter the pixel detector. The tracks are found as track segments that span three tracking stations, and are referred to as "inner triplets". Similarly, "outer pixel clusters" are used to find three-station track segments where the tracks exit the pixel detector, and are referred to as "outer triplets". To find inner triplets the trigger algorithm considers pairs of pixel clusters in two adjacent tracking stations. The inner pixel clusters in one tracking station are paired with all clusters in a neighboring station. Pairs of clusters that project into the beam region, signifying the beginning of a track, are passed to the next stage of the algorithm. Pairs of clusters that do not project into the beam region (i.e. those that project into the active area of the next tracking station or outside the detector) are dropped. The cluster pairs that are kept are combined with pixel clusters from a third tracking station in the next stage of the algorithm. We use the cluster pairs to create a search window in the third station. Cluster pairs that are successfully matched with a pixel cluster in the search window are passed as triplets to the final stage of the pattern recognition algorithm. In the final stage, the inner triplets, which consist of pixel clusters from three stations in the bend view, are matched with pixel clusters from the corresponding non-bend view stations. This stage of the algorithm improves the measurement accuracy for tracks at their entry point into the pixel detector.

This completes the pattern recognition for inner triplets. Outer triplets are found in a similar manner, except that the first stage of the algorithm keeps pairs of pixel clusters that project outside the fiducial volume of the pixel detector (instead of those that project into the beam region). A second difference is that outer triplets are not matched to pixel clusters from the non-bend view, since improved measurement accuracy is not required for outer triplets.

All stages of the pattern recognition are performed by FPGAs operating in parallel on pixel data associated with a single beam crossing. Subsequent operations that entail track reconstruction, vertex reconstruction, and the final trigger decision are handled by DSP farms. A DSP belonging to the farm that handles track reconstruction receives the inner and outer triplets found in one quadrant for a single beam crossing. Consequently, four DSPs operate in parallel to reconstruct the tracks for one beam crossing. These tracks are then brought together in a DSP that belongs to the vertex reconstruction farm. After completing the vertex reconstruction and imposing cuts for event selection, the DSP generates a "Level 1 accept" if the data for this beam crossing satisfy the selection criteria, or a "Level 1 reject", if not. If a Level 1 accept is generated, then data for the beam crossing are sent to a Level 2 processor for more refined calculations and selection requirements, otherwise the data are dropped. Fig. 3 shows the trigger efficiency that we achieve at Level 1 for a particular B_s decay mode that we have studied in great detail versus the rejection for minimum bias events (with an average of two events per beam crossing). The arrows in the figure indicate our current Level 1 vertex cut.

4. Concurrent development of the vertex detector and trigger

The designs of the BTeV pixel vertex detector and the Level 1 trigger have changed somewhat during the past few years as we have learned more about silicon pixel detectors and studied various trigger algorithms. It should not be all that surprising that changes in the pixel detector have had a direct influence on the pattern recognition for the trigger, since the pixel data are input to the trigger. However, our understanding of the Level 1 trigger has also had an impact on the design of the pixel detector.

The best example of how a change in the geometry of the pixel detector had a significant impact on the design of the Level 1 trigger is in the number of pixel planes per tracking station. In earlier designs of the pixel detector (described in the BTeV Preliminary Technical Design Report [4]) and trigger [5] we considered three pixel planes per tracking station, and a trigger that found track mini-vectors for each three-plane station in the pixel detector. Eliminating one of the three planes for every tracking station was a desirable goal for BTeV, since it would lead to a significant reduction in the amount of material in the detector. But before a two-plane design could be adopted, a workable trigger scheme that achieved a level of performance comparable to the earlier design had to be developed. With only two planes per station, track mini-vectors were abandoned and various new ideas for pattern recognition were studied. The design that emerged from these studies was

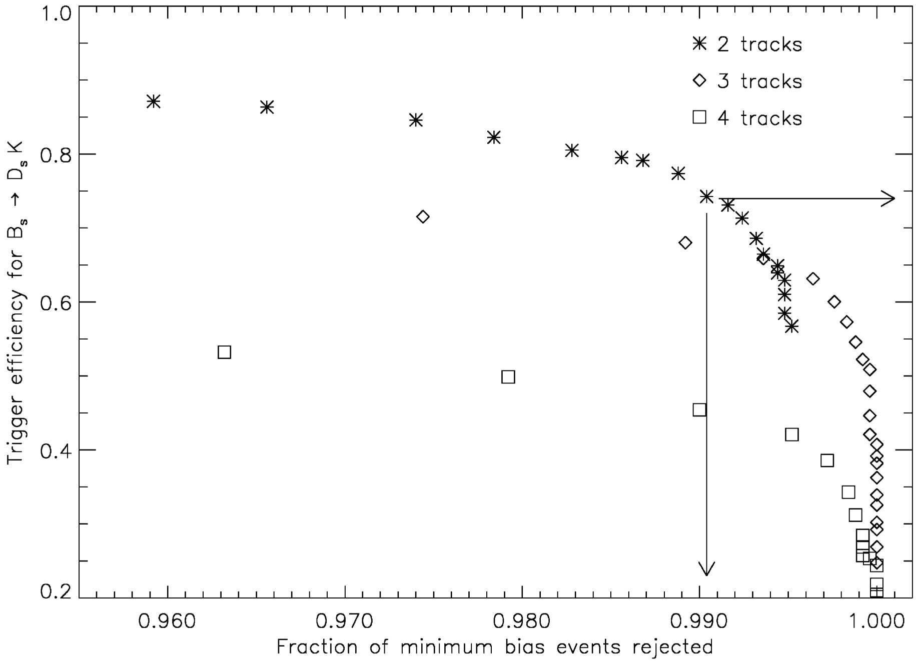

Fig. 3. Trigger efficiency for $B_s \to D_s^+ K^-$ versus rejection for minimum bias events. The figure shows three sets of cuts requiring a minimum impact parameter for 2, 3, or 4 tracks. Increasing the impact parameter cut increases the fraction of minimum bias events that are rejected, and the arrows indicate the cut (2 tracks at 6σ) that we use to achieve 99% rejection.

simulated and tested extensively, and was shown to satisfy the requirements for a Level 1 trigger for BTeV. This is the design that is presented in this paper, and in the BTeV Proposal [1].

Moreover, the new Level 1 trigger may lead to further changes in the geometry of the pixel detector. We are currently studying a design in which the two-plane tracking stations have smaller pixel planes for the non-bend view compared to the bend view. This change is motivated by the observation that the new trigger algorithm does not require any non-bend view pixel clusters for outer triplets. The change to the pixel detector would further reduce the amount of material in the pixel detector, and may simplify fabrication of the detector.

5. Conclusion

BTeV requires concurrent development of the pixel vertex detector and Level 1 trigger, since the two systems are interdependent. Changes in the vertex detector that modify the data that are sent to the Level 1 trigger usually require that changes be made to Level 1 algorithms. This is not surprising. However, we note that changes in the trigger algorithms can in turn influence the design of the vertex detector. By taking advantage of this interdependence and by linking the development effort for the two systems, substantial improvements can be achieved in the overall design of the experiment.

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