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THE CDF SILICON VERTEX TRIGGER FOR B PHYSICS STUDY

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1. Introduction

Charged particle trajectory reconstruction is a very common task in High Energy Physics (HEP) experiments. The history of HEP could be traced along the evolution of detectors and techniques employed to improve the resolution on track parameters. The typical processing time scale has evolved from months (in bubble chamber experiments) down to tenths and hundredths of second (in modern DAQ systems) in a non-monotonic way.

The need for even faster tracking tools stems from two main issues:

- The fact that experiments are carried out to measure smaller and smaller cross sections. This means an increase in the event rate, as a consequence of improvements both in detectors and accelerators.
- The finer granularity of modern detectors, needed to achieve a good track resolution. This means that experiments, especially those performed at hadronic colliders, are facing the need of more and more efficient triggering devices.

Silicon Vertex Tracker (SVT) has been designed as a high-efficiency triggering device for events involving the production of long-lived particles (like, for example, B-meson production).

B hadrons of sufficiently high transverse momentum are characterized by a large mean value of distribution of the impact parameter with respect to the beam axis. This means that events containing this kind of particles can be recognized and separated from non-long-lived background simply cutting on the track's impact parameter.

Tracking is in fact an essential ingredient for B physics studies, where long-lived particles (the B meson travels about 450 μm in the CDF environment) can be detected if a good enough tracking resolution is available. Up to now this resolution could only be efficiently achieved in the offline analysis, and was not exploited at trigger level.

One of the goals of CDF in Run II is to achieve online tracking resolution of the same order of magnitude as the offline; this might prove to be essential in order to be able to deal with the small ratio between the *b* quark production cross section and the total inelastic $p\bar{p}$ cross section. Single-track parameters (impact parameter in particular) are the most commonly used handles for the selection of *b*-flavored events.

The ability to trigger on this kind of events will extend the sensitivity to new phenomena, broaden the inventory of heavy flavor decay channels and provide important control samples for top quark related measurements.

2. The CDF Framework

The Collider Detector at Fermilab - CDF is a general-purpose experiment for the study of $p\bar{p}$ collisions at a center of mass energy of $\sqrt{s}$ = 1.8 TeV at the Fermilab Tevatron collider. The collider and detector performance have evolved from 1985 to today, meeting and surpassing the design goals. The needs of more performing tools have led to the current detector and collider improvements, which will be applied in Run II.

The Tevatron collider is planned to reach a luminosity of $2 \cdot 10^{32}$ cm^{-2} s^{-1}, $\sqrt{s}$ = 2.0 TeV, a minimum inter-bunch time of 132 ns with the mean number of overlapping events ranging between 2 and 6. The CDF detector is concurrently being upgraded to exploit the full power of the new collider, with the goal of accumulating 2 fb^{-1} of integrated luminosity.

The SVT project [1] is an essential part of a principal significance of the effort of redesigning the trigger system to work at the increased event rate while improving and expanding the triggering capabilities.

2.1 The CDF Tracking

The detector is described in detail elsewhere [2]. Here we will only outline the heart of the CDF tracking system: the COT and SVX-II detectors. The tracking systems are contained in a superconducting solenoid (1.5 m in radius and 4.8 m in length) generating a 1.4 T magnetic field parallel to the beam axis. In order to obtain a good resolution on the track parameters, two different detectors are used:

- The Central Outer Tracker (COT): a large open cell drift chamber designed to significantly outperform in response time its Run I predecessor (usually referred to as CTC).
- The Silicon VerteX detector (SVX-II): a 5-layer silicon microstrip detector, placed near to the interaction region.

The combined use of information from these detectors allows CDF to obtain an impact parameter resolution $\sigma_d \approx 30\ \mu m$. The new DAQ system has been designed to lower dead time as much as possible.

2.2 The CDF Trigger Structure

The whole CDF trigger and readout system is a three level pipelined dead-timeless device (with 5.5 μs and 20 μs latency time for the first two levels). Each decision stage selects events on the basis of the data available at that stage of the pipeline: for example COT data is available at the earlier stage (Level 1) while the first SVX-II information is available at Level 2. A tracking engine for the COT (XFT, eXtremely Fast Tracker) is implemented at Level 1, while SVT is designed to exploit XFT output and the SVX-II data, thus working at Level 2.

2.3 SVT Resulting Constraints

Since we want to identify as many events as possible, SVT needs to be implemented as early as possible in the CDF pipeline. On the other hand SVT needs SVX-II data to be available and thus cannot be earlier than Level 2. The total Level 2 latency is 20 μs on average, with 10 μs reserved for the Level 2 processors, and thus about 10 μs available for SVT processing. This defines the time constraints for SVT.

The resolution must be good enough to trigger on impact parameter and must therefore be of the same order of magnitude as the offline analysis.

3. SVT tracking strategy

The SVT separates the phases of pattern recognition and track fitting into two pipelined stages. Pattern recognition is performed by the Associative Memory system, which identifies low-resolution track candidates called "roads". The roads found by the Associative Memory and the full resolution hits corresponding to them are passed to the Track Fitters, which calculate track parameters. This is done using a linearized fitting algorithm implemented in hardware. SVT basic architecture is presented in Fig. 1.

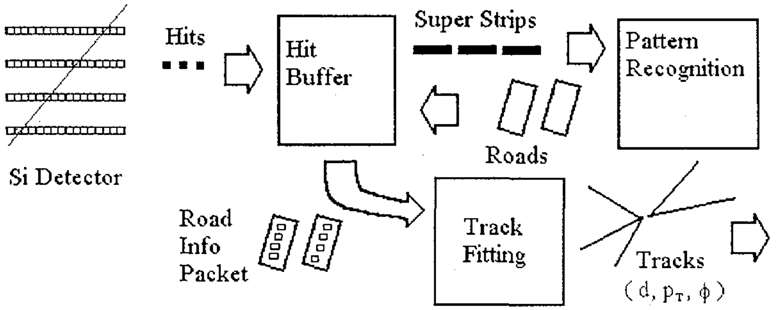

Fig.1 SVT basic architecture

3.1 Pattern recognition.

A track, which traverses a multilayer detector, produces a certain pattern of hits on each detector layer. Since detector resolution is finite, one could imagine to subdivide each detector layer in a finite number of elements with size comparable to resolution and to identify a track with the list of fired elements. Hit patterns corresponding to candidate tracks are stored in a memory, the Associative Memory, and are continuously compared in parallel to the data coming from the detector: a track candidate is found when all the hits corresponding to it are in the data.

The Associative Memory with a limited spatial resolution performs pattern recognition to reduce the size of the memory needed. For this purpose the Silicon Vertex Detector layers are segmented into 300 μm wide superstrips, while the actual strip pitch is 60 μm.

The Associative Memory functions are implemented in a full custom chip with 0.7 μm technology. Each chip can store 128 patterns containing 6 words (layers) of 12 bits. Operation of the chip has been tested up to 40 MHz, with the SVT specification being 30 MHz.

3.2 Track fitting

Track fitting is the problem of parameters reconstruction of the candidate tracks found in the phase of pattern recognition by the Associative Memory. The SVT reconstructs tracks projected on the plane transverse to the beam axis and measures transverse momentum, azimuthal angle and impact parameter (p_t, φ, d). Track parameters are expressed as scalar products:

$$p_i = \vec{f}_i \cdot \vec{x} + q_i \qquad (1)$$

where p_i is one of the track parameters and $\vec{x}$ is the array containing hit positions and track curvature and azimuthal angle. Within each 30^0 SVX wedge the parameters $\vec{f}_i$ and q_i are constants. Since variations of track parameters are small within a road, it is possible to expand p_i around a position x_0 in the hit space (typically the lower road edge). The following algorithm can thus be used:

$$p_i = \vec{f}_i \cdot (\vec{x}_0 + \vec{d}) + q_i \tag{2}$$

$$p_{0i} + \delta p_i = (\vec{f}_i \cdot \vec{x}_0 + q_i) + \vec{f}_i \cdot \vec{d} \tag{3}$$

where $p_{0i} = \vec{f}_i \cdot \vec{x}_0 + q_i$ and $\delta p_i = \vec{f}_i \cdot \vec{d}$. The advantage of this algorithm is that the p_{0i} can be pre-calculated and stored in a *look-up-table* reducing the computational load required by (1). Since $\vec{d}$ varies within the road edges (300 μm wide), a lower number of bits is necessary to have the full hit resolution.

SVT performance has been tested by reconstructing of the real CDF Run I data when using a bit-level simulation program of the device and it has been proven that track parameters are measured with offline quality resolution: $\sigma_{p_t} = 0.003 \cdot p_t^2$, $\sigma_\varphi = 1$ mrad and $\sigma_d \approx 30$ μm (at $p_t = 2$ GeV/c).

4. SVT architecture

The Silicon Vertex Detector is divided into 6 barrels along the z direction and each barrel in 12 wedges (sectors), each covering 30^0 in azimuthal angle. To maximize speed the SVT architecture resembles the SVX-II geometry. The SVT is made of 12 identical systems and each system processes data only from one SVX wedge (see Fig.2). All the systems run in parallel. The main functional blocks of each system are: Hit Finder, Associative Memory system, Hit Buffer and Track Fitter.

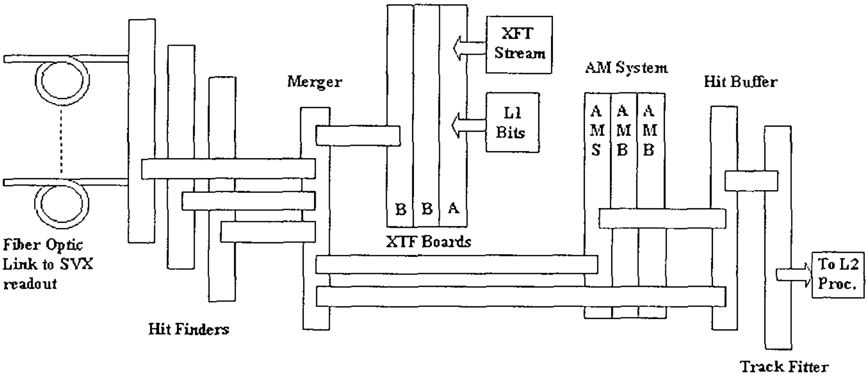

Fig.2 Board organization of an SVT wedge (1/12 of the whole system)

4.1 Hit Finder

The Hit Finder receives sparsified and digitized pulse heights from the SVX front-end electronics via optical G-links. Optical signals are converted to electrical at 53 MHz. The Hit Finder board synchronizes data coming from the G-links, subtracts pedestals and suppresses hot channels. Cluster centroids are found calculating the charge center of gravity. Since the number of silicon channels is very large, 3 Hit Finders are necessary for one 30^0 sector. Data output from the 3 Hit Finders corresponding to one sector are sent to a board called Merger, which merges them with the XFT track information. The Hit Finder has been successfully prototyped and tested at the specified speed of 30 MHz.

4.2 Associative Memory system

The Associative Memory (AM) system receives the silicon hits found by the Hit Finder and the XFT tracks, merged into one single stream by the Merger, and performs pattern recognition. The AM system is made of one control board (the Associative Memory Sequencer) and two Associative Memory boards. The AM system performs its function "on-the-fly" during detector readout and results are available shortly after the end of the input phase.

The Sequencer board interfaces the AM system to the rest of SVT and provides the proper operational codes to the Associative Memory boards through a custom P3 backplane. The AM board has two operating modes: "VME mode" and "Running Mode". VME mode is used to load patterns into the AM chip and for diagnostics and the board operates on an internal (slow) clock ignoring signals from the P3 backplane. In Running Mode the AM board is controlled and receives the clock from the AM Sequencer through the P3 bus.

Each AM board holds 128 AM chips: in running mode the board distributes the data and the op-codes to the chips and queues patterns output by the chips to the P3 bus. To this purpose two tree-like structures have been created, one for input and one for output, with the 128 chips at the bottom [3].

4.3 Hit Buffer

The Hit Buffer receives silicon hits and XFT tracks from the Merger and the roads from the AM Sequencer. Data from the Merger are received first, while the board is in "Write Mode". Data are sorted according to their superstrip number and stored in a structured database, called Hit List Memory, where each road number can then be used as a key to access lists of hits [4]. There is one Hit List for each superstrip and all these lists are filled as hits are received in input. The Hit Buffer has two operation modes: "Write Mode" and "Read Mode". In Write Mode the hits are organized in the Hit List Memory, in Read Mode the roads found by the AM system are used to access the Hit List Memory and retrieve all and only the hits corresponding to the roads found in the current event. The road and all the corresponding hits retrieved from the Hit List Memory make the road-info packet. The road-info packet is sent to the Track Fitter board, which performs the full resolution fit of the track.

4.4 Track Fitter

The main function of the Track Fitter is the calculation of the track parameters (p_t, φ, d) and the track χ^2. The linearized algorithm described in section 3.2 has been implemented in hardware.

5. SVT Timing

Timing performances have been estimated under the assumption that each board in the system will be able to operate at a 30 MHz rate and using the transit delay (input connector to output connector) measured on the real boards. A bit level simulation of the SVT has been used to reconstruct both real CDF data and simulated *b* jet events. Real data are from CDF Run I and thus correspond to Run I detector geometry, while Monte-Carlo data use Run II geometry. Estimated overall processing time is respectively 11 μs and 9 μs for *b* jet events generated at p_t > 20 GeV/c and p_t > 10 GeV/c, while for real data with a low expected content of *b* jets, time is 6 μs.

6. Physics triggers with the SVT

During Run I (1993-1996) B triggers of the CDF experiment were limited to the leptonic modes. Now the precision measurement of impact parameters from the SVT allows one to exploit more efficiently the huge Tevatron $b\bar{b}$ cross section (100 μb) and to design new triggers much better tuned on the geometry of B events (see Fig.3).

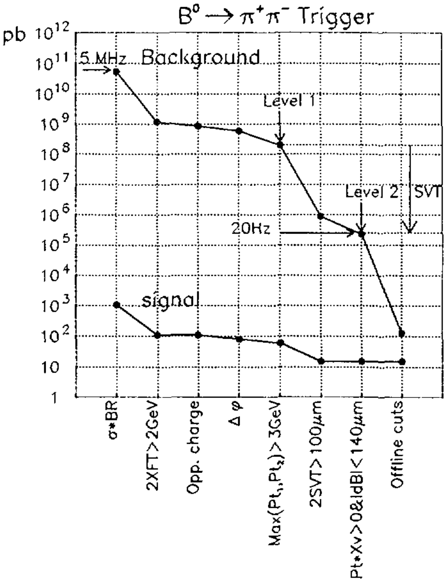

Fig.3 SVT reduces the background rate by a factor of 1000.

Let's stress that some of these triggers will allow study of the physics completely unavailable on the hadron colliders without SVT (e.g. $B^0 \rightarrow \pi^+\pi^-$). Other triggers demanding the presence of the secondary vertex in the event will allow us to reduce the lepton and jet cuts essentially increasing statistics.

For example, a trigger to select the hadronic decay $B^0 \rightarrow \pi^+\pi^-$ was studied, which is of a fundamental importance in the investigation of CP violation in the Standard Model [5].

The trigger selects two stiff (p_t > 2 GeV/c) opposite charge XFT tracks at Level 1, with some separation in the azimuthal angle ($\Delta\phi < 135^0$) in order to remove back-to-back pairs produced in 2-jet events. The trigger requires two SVT tracks with impact parameter greater than 100 μm and a positive decay length of the two-track vertex at Level 2. Simulation of the trigger using a detailed simulator of the SVT to reconstruct real CDF data from Run I and the extrapolation to Run II configuration shows that Run II trigger rates are well within DAQ bandwidth. The expected signal yield is of the order of 15000 events in 2 fb^{-1}, assuming a branching ratio for $B^0 \to \pi^+\pi^-$ of 10^{-5}.

Further studies have shown that with very small modifications of the cuts, the trigger is effective also in the selection of multi-body decay channels useful to measure the B^0_s mixing. The channels are $B^0_s \to D^-_s\pi^+$, $B^0_s \to D^-_s\pi^+\pi^-\pi^+$, with the D_s fully reconstructed through the hadronic decays $D^-_s \to \phi\pi^-$ and $D^-_s \to K^{*0}K^-$. The estimated signal yield is 25000 B^0_s decays in 2 fb^{-1} [6].

More recent studies have shown how to optimize the $B^0 \to \pi^+\pi^-$ trigger to select $\mathrm{Z}^0 \to b\bar{b}$ events. A low statistics $\mathrm{Z}^0 \to b\bar{b}$ signal has been observed at CDF in Run I data [7]. A high statistics of these events would be extremely useful in Run II to improve the b-jet energy calibration and consequently the resolution of the measurement of top mass. Moreover, the $\mathrm{Z}^0 \to b\bar{b}$ trigger would also increase CDF sensitivity to new heavy particles decaying to $b\bar{b}$.

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