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THE CDF-II ONLINE SILICON VERTEX TRACKER

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Abstract

The Online Silicon Vertex Tracker is the new CDF-II level 2 trigger processor designed to reconstruct 2-D tracks within the Silicon Vertex Detector with high speed and accuracy. By performing a precise measurement of impact parameters the SVT allows tagging online B events which typically show displaced secondary vertices. Physics simulations show that this will greatly enhance the CDF-II B-physics capability. The SVT has been fully assembled and operational since the beginning of Tevatron RunII in April 2001. In this paper we briefly review the SVT design and physics motivation and then describe its performance during the early phase (April-October 2001) of run II.

1 INTRODUCTION

CDF (Collider Detector at Fermilab) is a general purpose detector designed to study the high energy $p\bar{p}$ interactions produced at the Tevatron Collider. The Tevatron has recently completed major upgrades to achieve higher energy (990 GeV per beam) and instantaneous luminosity ($10^{32}\ cm^{-2}s^{-1}$). CDF has been upgraded to CDF-II to cope with the higher interaction rate as well as to extend its physics reach in this new and more difficult environment [1].

The CDF upgrades relevant for this paper are the tracker and the trigger. The tracker is composed of the Central Drift Chamber (COT) and three independent silicon detectors (Layer00, Silicon Vertex Detector and Intermediate Silicon Layers detector). The Layer00 is made of one layer of radiation hard silicon microstrips (with $r-\phi$ readout) placed just outside of the beam pipe ($r = 1.5$ cm). The new Silicon Vertex Detector (SVXII) [2, 3] is made of five double-sided (with $r-\phi$ and $r-z$ readout) microstrip sensors arranged in a 12-fold azimuthal geometry and segmented in 6 longitudinal barrels (3 mechanical units, each read out at both ends) along the beam line (CDF z-axis). The silicon layers are posed between 2.5 and 10.6 cm from the beamline. With the length of about 1 meter the SVXII covers 2 units in pseudorapidity. The ISL is located between the SVXII and the COT with one central layer at 23 cm from the beamline and two forward/backward layers respectively at 20 and 29 cm from the beamline. The COT is a multilayer drift chamber which covers the region between 46 cm and 131 cm from the beamline. It provides a high resolution measurement of the curvature and azimutal angle of the charged tracks.

The CDF trigger has been completely rebuilt and it consists of three levels. Its challenging task is to reduce the 5 MHz rate input to level 1 to the 50 Hz allowed as maximum output rate from level 3 which is written directly to tape. Levels 1 and 2 are implemented in hardware while level 3 is an executable running on a PC farm. The level 1 device most relevant to this paper is the eXtremely Fast Track finder processor (XFT) [4] which reconstructs 2-D tracks (in the $r-\phi$ plane, transverse to the beam line) in the central drift chamber (COT). The Online Silicon Vertex Tracker (SVT) is part of the level 2 trigger. It receives the list of COT tracks reconstructed by the XFT processor (for each track the curvature c and azimutal angle ϕ are measured) and the digitized pulse heights on the silicon layers ($\sim 10^5$ channels). The SVT links the XFT tracks to the

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silicon hits and reconstructs tracks with offline-like quality. From simulation of the tracking algorithm on run I data the expected resolution of the SVT is $\delta\phi \simeq 1$ mrad, $\delta P_t \simeq 0.003 \cdot {P_t}^2$ GeV/c, $\delta d \simeq 35\ \mu m$ (d is the track impact parameter, i.e. the distance of closest approach of the particle trajectory elix to the z-axis of the CDF reference system).

By providing a precision measurement of the impact parameter of charged particle tracks SVT allows triggering on events containing long lived particles. B hadrons in particular have a decay length of the order of 500 microns and tracks which come out of the B decay vertices have an impact parameter on average greater than 100 microns. The opportunity offered by the SVT of triggering directly on B hadron decay vertices is available for the first time at a hadron collider. It greatly improves the capability of selecting online B events which was tightly bound to leptonic decay modes in the past. Given the very large cross section for producing B hadrons of the Tevatron (100 microbarn), CDF-II expects to have access even to rare purely hadronic B decays like $B^\circ \rightarrow \pi\pi$ and $B_s \rightarrow D_s\pi \rightarrow$ hadrons, which are extremely interesting respectively for CP violation and B_s mixing measurements.

2 SVT WORKING PRINCIPLE

The SVT has a very short time to keep up with the 50 KHz level 1 accept rate and to perform its task (on average about 20 μs per event). For this reason the whole SVT design has been concentrated on speeding up operations. The SVT has a widely parallelized design: it is made of 12 identical azimuthal slices ("wedges") working in parallel. Each wedge receives and processes data from only one SVXII 30° wedge. In addition the SVT reconstructs only tracks in the transverse plane to the beamline (stereo info from SVXII is dropped) and only with p_t above 2 GeV/c.

The tracking process is performed in two steps:

- Pattern recognition: candidate tracks are searched among a list of precalculated low resolution patterns ("roads");
- Track fitting: a full resolution fit of the hit coordinates found within each road is performed using a linearized algorithm;

The pattern recognition step is performed in a completely parallel way by the Associative Memory system which uses full custom VLSI chips (AMchips [5]). The AM system compares all the silicon clusters and XFT tracks with the set of precalculated patterns. A pattern is defined as a combination of five bins ("SuperStrips"): four SuperStrips correspond to the position coordinates of the particle trajectory on four silicon layers, which can be chosen among the five SVXII layers and Layer00, the fifth SuperStrip corresponds to the azimuthal angle of the particle trajectory at a distance of 12 cm from the beam line. The output of AM system is the list of patterns ("roads") for which at least one hit has been found on each SuperStrip. Each SVT wedge uses 32K patterns which cover more than 95% of the phase space for $p_t \geq 2$ GeV/c. Simulation studies have shown that SVT performance is optimized (in terms of processing time and final resolution) by choosing a SuperStrip size of about 250 micron on the silicon layers and 5° for the ϕ angle measured by XFT.

The track fitting method is based on linear approximations and principal component analysis [6]. The analytical relationship between the track parameters and the six measured hit coordinates (hit positions on four silicon layers, curvature, and azimuthal angle of XFT track) can be expressed in terms of six equations:

$$P_j = P_j(\mathbf{x}) = \mathbf{F}_j \cdot \mathbf{x} + Q_j \qquad (1)$$

where $\mathbf{x}$ is the vector of hit coordinates and $\mathbf{P}$ = (d,c, ϕ, χ_1, χ_2, χ_3) are respectively the impact parameter (d), the curvature (c) and the azimuthal angle (ϕ) at the point of minimum approach to the z-axis, while χ_1, χ_2 and χ_3 are three independent constraints which all real tracks must satisfy (within detector resolution effects). $\mathbf{F}_j$ and Q_j are constants which depend only on the detector geometry and the magnetic field.

After pattern recognition has been performed each track candidate is confined within one road and this information can be used to simplify the computation of equation 1. The hit coordinates and track parameters are given by the sum of a term which depends only on the SuperStrip edge ($\mathbf{x_0}$) and an additional term ($\delta\mathbf{x}$) which depends on the posistion of the hits within the SuperStrips. Equation 1 becomes:

$$P_{0j} + \delta P_j = \mathbf{F}_j \cdot (\mathbf{x_0} + \delta\mathbf{x}) + Q_j \qquad (2)$$

where, $P_{0j} = \mathbf{F}_j \cdot \mathbf{x_0} + Q_j$ is a constant which depends on the single road, while δP_j is the correction which depends on the precise hit positions inside the road. The P_{0j} coefficients are calculated offline, stored in RAMs and used on a track-by-track basis. Therefore the track fitting task reduces to the fast computation of simple scalar products (done by FPGA chips)

$$\delta P_j = \mathbf{F}_j \cdot \delta\mathbf{x}. \qquad (3)$$

which determine the small correction to add to the road dependent constant terms. The SVT output is the list of high precision tracks which is sent to the trigger processors for the final level 2 trigger decision.

SVT comprises over one hundred VME boards housed in eight crates [7]. The installation has been completed and the system has been fully operational since the beginning of 2001. In the following section we report on the performance achieved by the system in the early phase (April-October 2001) of run II.

3 SVT PERFORMANCE

The correlation of the impact parameter d versus the azimuthal angle ϕ of candidate tracks (Figure 1 (*top*)) is the first evidence that the SVT tracks are good. The plot shows

the typical sine wave shape which is due to the fact that the position of the interaction vertex in the transverse plane (x_0, y_0) is displaced from the origin of CDF reference system. In this case the relationship between d and ϕ for primary tracks is:

$$d = -x_0 sin(\phi) + y_0 cos(\phi). \quad (4)$$

A fit to the $d-\phi$ scatter plot provides a measure of the (x_0, y_0) coordinates with an accuracy of few microns.

A beam displacement of a few millimiters is a typical running condition for CDF. In principle this condition could be a problem because it generates unphysical large impact parameters which are erroneously interpreted by the level 2 trigger as the presence of B decays. In practice this potential problem is avoided by having a process running on the SVT VME crate controller and performing a fit of the $d-\phi$ correlation to determine the beam offset. The beam position parameters are transferred to the SVT which subtractes the beam offset internally (Figure 1 (*bottom*)). To remove possible additional misalignments among SVXII barrels, this is done independently for tracks in each of the six SVXII z-barrels. Following this procedure the level 2 trigger receives physical impact parameters (i.e. measured with respect to the actual beam position). Figure 2 shows the impact parameter distribution after correcting for the beam offset. This distribution is given by the convolution of the actual transverse beam profile with the intrinsic impact parameter resolution. A gaussian fit gives $\sigma \simeq 69$ micron.

A big effort has been put in understanding the various factors which contribute to the SVT impact parameter resolution. The goal is to improve it as much as possible, because the worse the resolution is the higher is the rate of the triggers based on impact parameter cuts. The potentially most relevant contribution to the d resolution arises from the z-misalignment between the detector and the beam. The effect of a z-misalignment ($mx = \delta x/\delta z$, $my = \delta y/\delta z$) shows up as a residual modulation in the impact parameter $d-\phi$ correlation obtained after correcting for the beam offset:

$$d' = -m_x z_0 sin(\phi) + m_y z_0 cos(\phi) \quad (5)$$

where z_0 is the z-coordinate of the point of closest approach of the particle trajectory to the z-axis. Unfortunately z_0 is not measured by the SVT, which receives the only z information from the SVXII segmentation into six barrels, therefore the beam tilt results in an irreducible widening of the d distribution. In order to make this spread small compared to the natural beam width, SVT requires the detector and the beam to be parallel within 100 μrad. Assembly of the SVXII barrels indeed met this specification [3], The alignment of the beam orbit turned out to be more challenging. During the April-October data taking period, the beam slope was significantly large: $m_x \simeq 600$ μrad, $m_y \simeq 150$ μrad, well beyond the SVT specification. The effect of the z-misalignment on the impact parameter distribution was estimated using a special run taken with an approximately null beam tilt. In this case the d distribution had $\sigma \simeq 59$ micron, which is 10 microns smaller than the width found for the runs taken with significant beam tilt. Work is in progress in order to have a good alignment as the standard running condition.

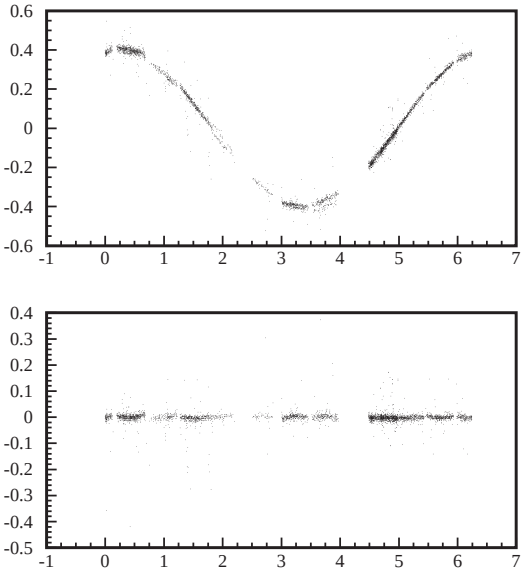

Figure 1: $d-\phi$ correlation for SVT track candidates before (top) and after correcting for beam offset ($bottom$). The average beam position in the transverse plane is measured with a fit to the top plot (x_0=0.0995 cm and y_0=-0.3895 cm) with a precision of $\simeq 3$ micron. The regions without points around ϕ=2.2 and ϕ=4.2 rad are due to SVXII wedges which were turned off when the data analysed in this paper were taken. The scale on the x axis is radians, the scale on the y axis is cm.

There are two additional major contributions affecting the impact parameter resolution. The first is the relative misalignment among SVXII wedges. This contribution can be easily corrected by performing the beam position fit and the corresponding impact parameter beam offset subtraction independently in each wedge. The size of this correction to the resolution is approximately 6 micron. The second contribution to the impact parameter resolution is a consequence of the linear approximation of the SVT track fitting method, which assumes a first order expansion centered at the beam position. Since during the April-October data taking the beam was very far from its nominal position ($\simeq 4$ mm away) the effect of non linearity was significant: it reduced the impact parameter resolution by approximately 5 micron. This effect can be corrected by recalculating the constants used in equation 2 centering the expansion on the measured beam position. After applying all these corrections the impact parameter distribution was found to have a gaussian shape with a sigma of 48 microns for a run taken with the beam aligned in z [1]. All these corrections can be

[1]There are additional effects: a residual non linearity in d and ϕ, and the misalignement of silicon layers within a wedge. The correction for these effects is less straightforward because it requires reprogramming some SVT boards and adjusting the detector geometry of the SVT maps. The

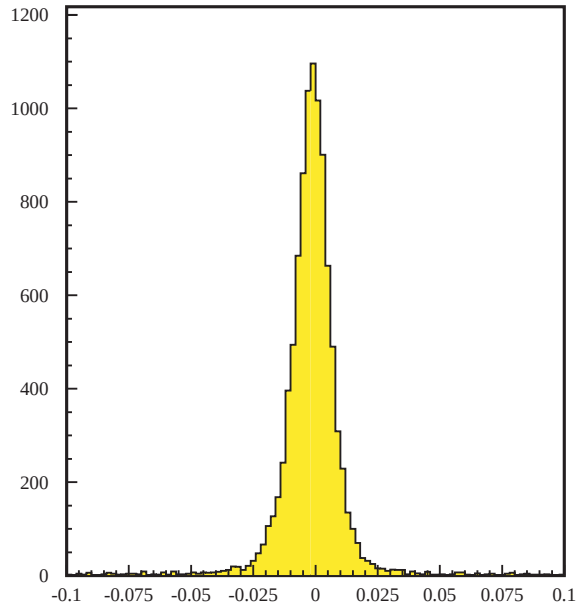

Figure 2: Impact parameter distribution (scale is cm) after correcting for the beam offset.

easily implemented in the SVT by modifying the constants loaded on the boards. They will be implemented in the next data taking after the October shutdown. The only ingredient out of the SVT control is the beam alignment along z.

As anticipated the impact parameter distribution is the convolution of the actual transverse beam profile with the intrinsic impact parameter resolution. By using equation (4) it can be shown that the covariance of the impact parameters of two tracks originating from the same vertex is proportional to the cosine of the opening angle between the two tracks:

$$\sigma_{d_1 d_2} =< d_1 \cdot d_2 >= \sigma_B^2 \cdot \cos(\Delta\phi) \qquad (6)$$

where the constant σ_B is the width of the actual transverse beam profile. By using this relation and October 2001 data it has been possible to measure the beam width (33 microns) and consequently determine the intrinsic impact parameter resolution of the SVT (35 micron) by subtracting in quadrature σ_B from the impact parameter distribution width (48 micron). The estimate for the SVT impact parameter resolution is well in agreement with early SVT performance simulations.

4 PHYSICS PROSPECTS WITH THE SVT

CDF has designed a trigger strategy ("hadronic B trigger") based only on tracking to select hadronic B decays interesting for CP violation and B_s mixing. The idea is to select charmless decays ($B_d^0 \rightarrow h^+h^-$) for CP violation and a collection of charmed decays ($B_s^0 \rightarrow D_s^-\pi^+$ and $B_s^0 \rightarrow D_s^-\pi^+\pi^-\pi^+$ with the $D_s^- \rightarrow \phi\pi^-$ and $D_s^- \rightarrow K^{*\circ}K^-$) for mixing. This trigger strategy relies on XFT tracks at level 1 and SVT tracks at level 2. The most important ingredient are the level 2 impact parameter cuts which reduce the trigger rate by three orders of magnitude. For the success of this trigger strategy the SVT performance is essential.

In October 2001 CDF took the first test runs which implemented a simplified version of the hadronic B trigger. The level 1 required two opposite charge XFT tracks with $p_t > 2$ GeV/c, $p_{t1} + p_{t2} > 5.5$ GeV/c and an opening angle smaller than 135°. The level 2 required two good SVT tracks with $p_t > 2$ GeV/c (no impact parameter threshold was set for these preliminary test runs). Using this data ($\simeq 15$ nb^{-1}) and a very simple selection based on decay length cuts, a small signal of $D^\circ \rightarrow K\pi$ was reconstructed [6] (Figure 2). Although this is not a fully reconstructed hadronic B signal yet, it shows that the purity of the triggered sample allows extracting some heavy flavour signal even from a very small sample (15 nb^{-1}). As data taking proceeds we expect to perform more sophisticated analysis and to isolate the first hadronic B signals. With the 2 fb^{-1} of data CDF-II plans to collect in run II we expect to contribute significantly to the field of CP violation in B decays and B_s mixing.

5 CONCLUSIONS

The Online Silicon Vertex Tracker is the new level 2 trigger processor dedicated to the reconstruction of tracks within the tracking chamber and the silicon vertex detector of the CDF-II experiment. The SVT has been successfully installed and operated during the preliminary phase of run II. The performance of the device has already shown to be very close to the design. The impact parameter resolution is as

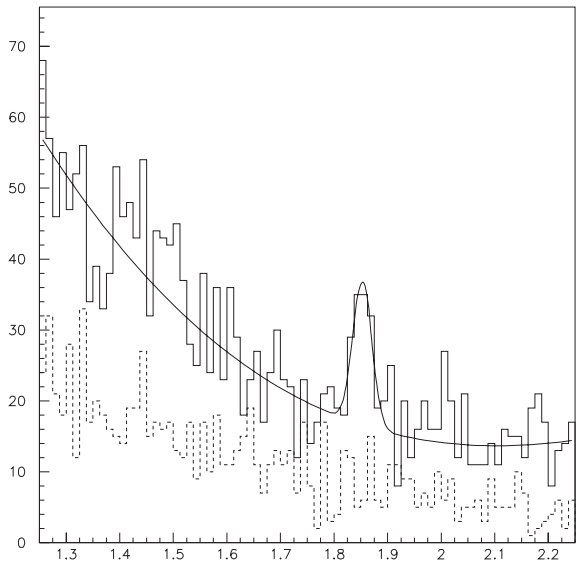

Figure 3: Invariant mass distribution for track pairs assuming the two tracks to be π and K, and applying cuts optimized to select a $D^\circ \rightarrow K\pi$ signal. The scale of the horizontal axis is GeV/c^2.

effect of these additional correction has been studied with the simulation and reduces the the width of d distribution to 45 micron.

good as needed for a successful operation of the trigger provided that the tilt between the beam and the detector is not larger than 100 microradians. CDF relies on SVT tracks for trigger strategies dedicated to the selection of hadronic B decays. Preliminary test runs implementing these strategies have been taken in October 2001 and the first signals of heavy flavours have been found. Improvements of the SVT performance are expected in the near future as the operating conditions will evolve from the commissioning to a more stable phase. Pedestal adjustments, dead channels suppressions and a better tuning of the clustering algorithm are expected. Fine tuning of the SVT (corrections for non-linearities and relative wedge-to-wedge misalignments) will soon be implemented.

6 REFERENCES

[1] J. Spalding, *Run-II upgrades and physics prospects*, to be published in the Proceedings of the 7^{th} International Conference on Advanced Technology and Praticle Physics, Villa Olmo, Como, October 15-19, 2001.

[2] S. D'Auria, *Commissioning and Operation of the CDF Silicon Detector*, to be published in the Proceedings of the 7^{th} International Conference on Advanced Technology and Praticle Physics, Villa Olmo, Como, October 15-19, 2001.

[3] F. Palmonari, *The CDF-II Silicon Tracking System*, to be published in the Proceedings of the 7^{th} International Conference on Advanced Technology and Praticle Physics, Villa Olmo, Como, October 15-19, 2001.

[4] C. Ciobanu *et al*, *Online Track Processor for the CDF Upgrade*, IEEE Trans. Nucl. Sci., vol. 46, pp. 933-939, 1999.

[5] S.R. Amendolia *et al*, *The AMchip: a Full-custom CMOS VLSI Associative Memory for Pattern Recognition*, IEEE Trans. Nucl. Sci., vol. 39, pp. 795-797, 1992.

[6] W. Ashmanskas *et al*, *Performance of the CDF Online Silicon Vertex Tracker* to be published in IEEE Trans. Nucl. Sci. (2001).

[7] S. Donati *et al*, *The CDF Silicon Vertex Tracker: Online Precision Tracking of the CDF Silicon Vertex Detector*, Il Nuovo Cimento, vol. 112A n.11, pp. 1239-1243, 1999.