The CDF Online

Silicon Vertex Tracker

Or Secondary Vertex Trigger

R. Carosi
INFN Pisa

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Outline

• Physics motivations and the CDF detector
• Displaced tracks and impact parameter
• Principles of SVT
• Pattern recognition
• Track fitting
• The future
The Tevatron and CDF Upgrades for Run II

- New Tracking System
  - COT
- L00 +SVXII + ISL
  - 3-D info
  - Extended tracking to forward region
- New Trigger
The SVXII detector

6 electrical barrels

6 half barrels in z
12 "wedges" in phi

Wedge symmetry:
Allows parallelism
CDF Trigger in run II

- **Three levels of detail**

- **Level 1 (2.5 MHz - 25 kHz):**
  - 5.5 μsec
  - calorimeter, muons, **tracks**

- **Level 2 (25kHz-300 Hz):**
  - ~40 μsec
  - jet clustering, silicon **tracking**
  - **SVT**

- **Level 3 (300 Hz - 50 Hz):**
  - ~1sec/event
  - full-precision tracking
  - ~140 separate trigger paths
Why do we need the Silicon Vertex Tracker?

The Tevatron produces a lot of B events
\[ \sigma_{\bar{b}b} = 50 \, \mu \text{b} \quad (\sim 10^{11} \text{ events in Run II}) \]

But hidden in QCD background x1000
\[ \sigma_{\bar{p}p} = 50 \, \text{mb} \]

We need a Trigger

"The Old Way"
- Trigger on leptonic B decays
- SVX tracks used Offline to reconstruct Secondary Vertices

Problems
- Low B.R. for leptonic modes
- Detector acceptance limited

(Nonetheless, many results from CDF)

"The New way"
- SVT: trigger on displaced tracks

Improved B physics capabilities: fully hadronic B decays
Track reconstruction in the Trigger

- To trigger on impact parameter, we need to reconstruct tracks with good precision (comparable with offline tracking)
- Tracking must be fast enough (15-20us)
- Tracking is usually very time consuming
- Idea: use precalculated patterns
- In SVT, we perform 2D tracking (x-y plane)
  - 1st step: select hit combination that form tracks ("pattern recognition")
  - 2nd step: clean up and parameter calculation ("track fitting")
SVT: Silicon Vertex Tracker

SVT receives:
- COT tracks from Level 1 XFT ($\phi, P_T$) with $\sigma(q/P_T)=1.7\%/\text{GeV}$, $\sigma(\phi)=5\text{mrad}$.
- Digitized pulse height in SVXII strips.

Performs tracking in a two-stage process:

1. Pattern recognition:
   Search “candidate” tracks (ROADS) at low resolution.

2. Track fitting:
   Full resolution 2-D track fit with $\sigma(q/P_T)=1.0\%/\text{GeV}$, $\sigma(\phi)=1.5\text{mrad}$, $\sigma(d)=35\text{um}$.

SVX II geometry:
- 12 $\phi$-slices (30° each) “wedges”
- 6 modules in $z$ (“semi-barrels”)
The SVT Algorithm (Step I)

Fast pattern Recognition

- Hardware Implemented via the Associative Memory Chip (full custom - INFN Pisa):
  - Receives the list of hit coordinates
  - Compares each hit with all the Candidate Roads in memory in parallel
  - Selects Roads with at least 1 hit in each SuperStrip (found roads)
  - Outputs the list of found roads

- FAST! : pattern rec. is complete as soon as the last hit of the event is read
- 32,000 roads for each 30° slice
- ~250 micron SuperStrips
- > 95% coverage for Pt >2 GeV
Associative Memory working principle

AM = BINGO PLAYERS

Bingo scorecard
Summary of Pattern Recognition method

- Hit combinations that form possible tracks are precalculated and stored ("pattern bank")
- To make the bank small, low resolution bins are used
- Every hit is compared with each stored pattern in parallel
  - Small bins -> large bank -> lower background -> faster fit
  - Large bins -> small bank -> higher background -> slower fit
The SVT algorithm (Step II)

Track Fitting

- Track fitting is a mini pattern recognition confined to a Road
- Few hit combinations to check
- Clean up using a chi2 test and parameter calculation
- A 2D track is identified by 3 parameters (curvature, impact parameter and azimuthal angle: c, d, \( \varphi \))
- Each track is measured in 6 points: 4 Silicon layers and 2 measured by XFT (c, \( \varphi \) are considered as “points”)

\[
X_0 = f_0(c, d, \varphi) \quad \leftarrow 6 \text{ equations}
\]

\[
X_5 = f_5(c, d, \varphi)
\]

\((X_0 - 3: \text{Silicon}; \quad X_4-5: \text{XFT})\)

- Therefore there are 6-3=3 constraints to form a chi2
- Constraints and parameters are calculated using linear approximations
- Linear approximation are valid in a limited spatial region
- An SVX wedge is small enough (but...)
The SVT Algorithm (Step II)

Track Fitting

When the track is confined to a road, fitting becomes easy!

- Linear expansion of Parameters in the hit positions $X_i$:
  \[ P_i = F_i \times X_i + Q_i \quad (P_i = p_t, \phi, d, \chi_1, \chi_2, \chi_3) \]

- … then refer them to the ROAD boundary:
  \[ P_{0i} + \delta P_i = F_i \times (X_{0i} + \delta X_i) + Q_i \]
  \[ P_{0i} = F_i \times X_{0i} + Q_i \]

- $F_i$ and $P_{0i}$ coefficients are calculated in advance (using detector geometry) and stored in RAM.

- the task reduces to compute the scalar products (FPGA):
  \[ \delta P_i = F_i \times \delta X_i \]
The SVT Algorithm (Step II)

Track Fitting

6 coordinates: $x_1, x_2, x_3, x_4, x_5 (P_T), x_6 (\phi)$

3 parameters to fit: $P_T, \phi, d$

3 constraints $F(x_1, x_2, x_3, x_4, x_5, x_6) = 0$

Tangent plane:

$$\sum_{i=1}^{6} a_i x_i = b$$

Track parameters:

$$d \approx c_0 + \sum_{i=1}^{6} c_i x_i$$

Linear approximation is so good that a single set of constants is sufficient for a whole detector wedge (30° in $\phi$)
Track fitting: geometrical constraint

“Silicon-only” configuration:
4 points -> 1 constraint
(Commissioning run, Nov 2000)
How to calculate constants?

- Constants for parameters: use Monte Carlo generated tracks with known parameters and perform a fit.
- Constants for constraints: it can be proved that they are the eigenvectors corresponding to 0 eigenvalues of the hit covariance matrix ("Principal Component Analysis"):

\[ M_{ij} = \frac{\sum x(i) x(j)}{N} - \left( \frac{\sum x(i)}{N} \right) \left( \frac{\sum x(j)}{N} \right) \]
\[ M = \lambda v \quad \lambda \sim 0 \]

- Because of finite detector resolution, there are no 0 eigenvalues.
- We take the 3 lowest eigenvalues.
- In general we can check the number of independent variables.
- Each non-null eigenvalue corresponds to a parameter.
- Validity of linear approximations in a 30° wedge to be checked.
- We can use data to calculate constraints!
How good is the linear approximation?

For a circle tangent to the $x$ axis,

$$y = \frac{cr^2 + d(1 + cd)}{1 + 2cd}.$$  

Including $\phi \neq 0$ and using $|cd| < 10^{-4},$

$$y = \frac{cr^2}{\cos \phi} + r \sin \phi + \frac{d}{\cos \phi}.$$  

Silicon: constant $x$, not constant $r$:

$$y = \frac{c}{\cos^3 \phi} x^2 + x \tan \phi + \frac{d}{\cos \phi}.$$  

$\Rightarrow$

1. Fit is linear in $\tan(\phi)$, not $\phi$
2. up to 3.5\% scale error on $d$:
   3.5 $\mu$m at 100 $\mu$m (at 15°)
Summary of Track Fitting method

- Inside each pattern, good hit combinations are selected
- Constraints are used to calculate a chi squared
- Constraints and parameters (pt, phi, d) are calculated using linear approximation
- Linear approximations are good enough inside each phi wedge
- Constants are calculated using simulation
- Misalignment can be taken into account
The SVT Boards

Hit Finder

AM Sequencer

AM Board

Super Strip

Matching Patterns

Roads + Corresponding Hits

Detector Data

Hits

Rocks

Hit Buffer

Tracks + Corresponding Hits

L2 CPU

Track Fitter
SVT crate
Beam position fit

$d - \phi$ correlation

- Sinusoidal shape is the effect of beam displacement from origin of nominal coordinates

\[ d = X_0 \cdot \sin(\phi) - Y_0 \cdot \cos(\phi) \]

- Can find the beam consistently in all wedges even using only SVX track

\begin{itemize}
  \item raw
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    \end{center}
  \item subtracted
    \begin{center}
    \includegraphics[width=0.5\textwidth]{subtracted.png}
    \end{center}
\end{itemize}
Online Beam position

Full scale ~100 um, 400 urad, x4 days
Online Beam position II

CDF discovers gravity

Xbeam

Ybeam

dx/dz
dy/dz
Independent fit on each SVXII z-barrel (6)

This distribution is interpreted as the convolution of the actual transverse size of the beam spot with the impact parameter resolution of the SVT

$\sigma \sim 50 \mu m \sim 40 \mu m + 30 \mu m$

$\sigma = 50 \mu m$
Can extract $\sigma_B$ from the correlation between impact parameters of track pairs.

- If the beam spot is circular:
  \[
  \langle d1 \cdot d2 \rangle = \sigma_B^2 \cdot \cos \Delta \varphi
  \]
  \[
  \sigma_B = 40 \ \mu m
  \]
- But at present the beam is tilt (beam spot is an ellipsis):
  \[
  \sigma_{\text{short}} = 33 \ \mu m
  \]
  \[
  \sigma_{\text{long}} = 47 \ \mu m
  \]
Total timing: $A \cdot N_{hit} + B \cdot N_{comb} \cdot N_{roads} + C$

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<tr>
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<th>Data Processing</th>
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<td>Analog</td>
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<tr>
<td>Digital</td>
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<tr>
<td>Mergers</td>
<td>Final Decision</td>
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SVX readout   SVT proc.   Total (us)

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predicted

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actual
$B^0 \rightarrow \pi \pi$ Trigger

**Level 1**
- Background

**Level 2**
- SVT

**Signal**
- $\sigma_{\text{BR}}$
- $2\,\text{FT}>2\,\text{GeV}$
- Opp. charge
- Delta-phi
- $\text{Max}(\text{Pt}_1,\text{Pt}_2)>3\,\text{GeV}$
- $2\,\text{SVT}>100\,\text{um}$
- Pt-$x>0$ & Id-$b<140\,\text{um}$

**Pb**

Logarithmic scale from $10^0$ to $10^{12}$.
Invariant masses

CDF Run II Preliminary

$L = 9.6 \text{ pb}^{-1}$

$D^0 \rightarrow K\pi$

$N_{D^0} = 56320 \pm 490$

CDF Run 2 Preliminary

$L = 5.7 \text{ pb}^{-1}$

$D^\pm \rightarrow K\pi\pi$

$N_{D^\pm} = 25570 \pm 160$
Improvements

• When **efficiency** was an issue, “4 out of 5” in SVX
• Optimizations: optimal patterns (superstrip size) and geometry
• When the Tevatron luminosity increased, **timing** became an issue
• Optimal cuts to reduce the rate
• Skip events that do not need SVT
• Optimizations to reduce the timing
• Still a lot of work to be done
Larger Associative Memory:
  larger pattern bank
  smaller superstrips
  less work for the Track Fitter, better timing
• New (and better) electronics
• More flexibility (e.g. use different pattern banks)