Trigger and Displaced Vertexing

the CDF Silicon Vertex Tracker

Alessandro Cerri

CERN

Outline

- Motivation
- What is the SVT?
- How does the SVT work?
- Performances and future developments

Motivation

- SVT: hardware for high resolution tracking at early trigger stages
- Use cases:
  - Need for fast pattern recognition on large amounts of data:
    - Fine detector segmentation
    - High-occupancy
  - Heavy flavor physics (b, c)
  - New physics coupled to 3rd family (e.g. H➔bb, ττ etc.)

Pattern recognition hunger

Experiment	#Si Readout elements
CDF Run I	46K
CDF Run II	720K
ATLAS	>80M

•HEP experiments evolve to

- •finer and finer segmentation
- •Higher occupancy
- •Larger event rate

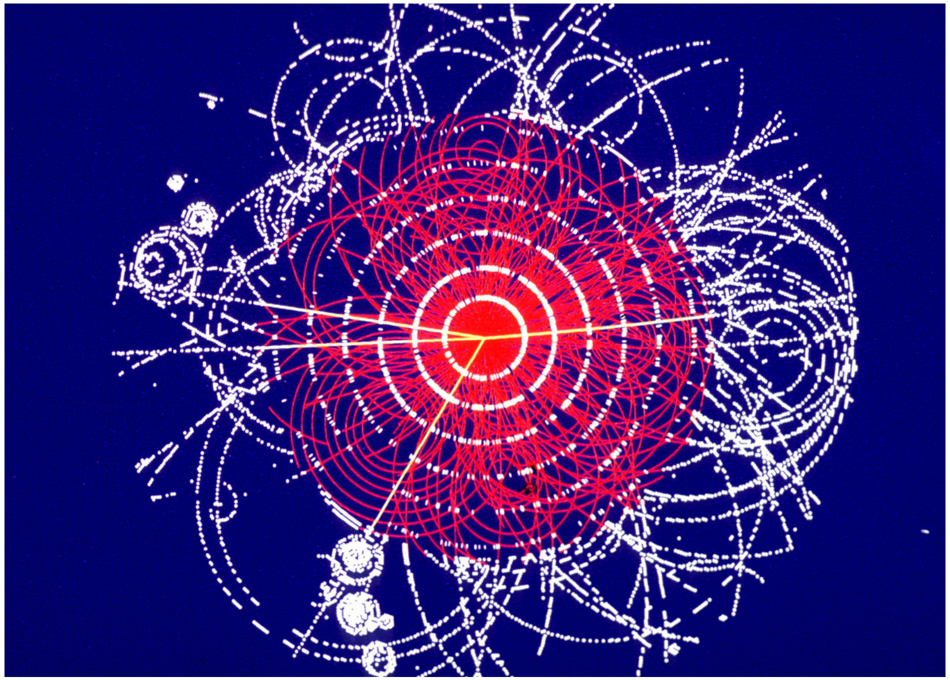
•Reading out and processing these large amounts of data often becomes unpractical

•SVT is a dedicated hardware processor

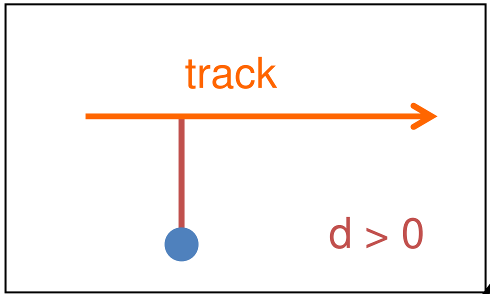
•Its philosophy can be applied to many pattern recognition problems:

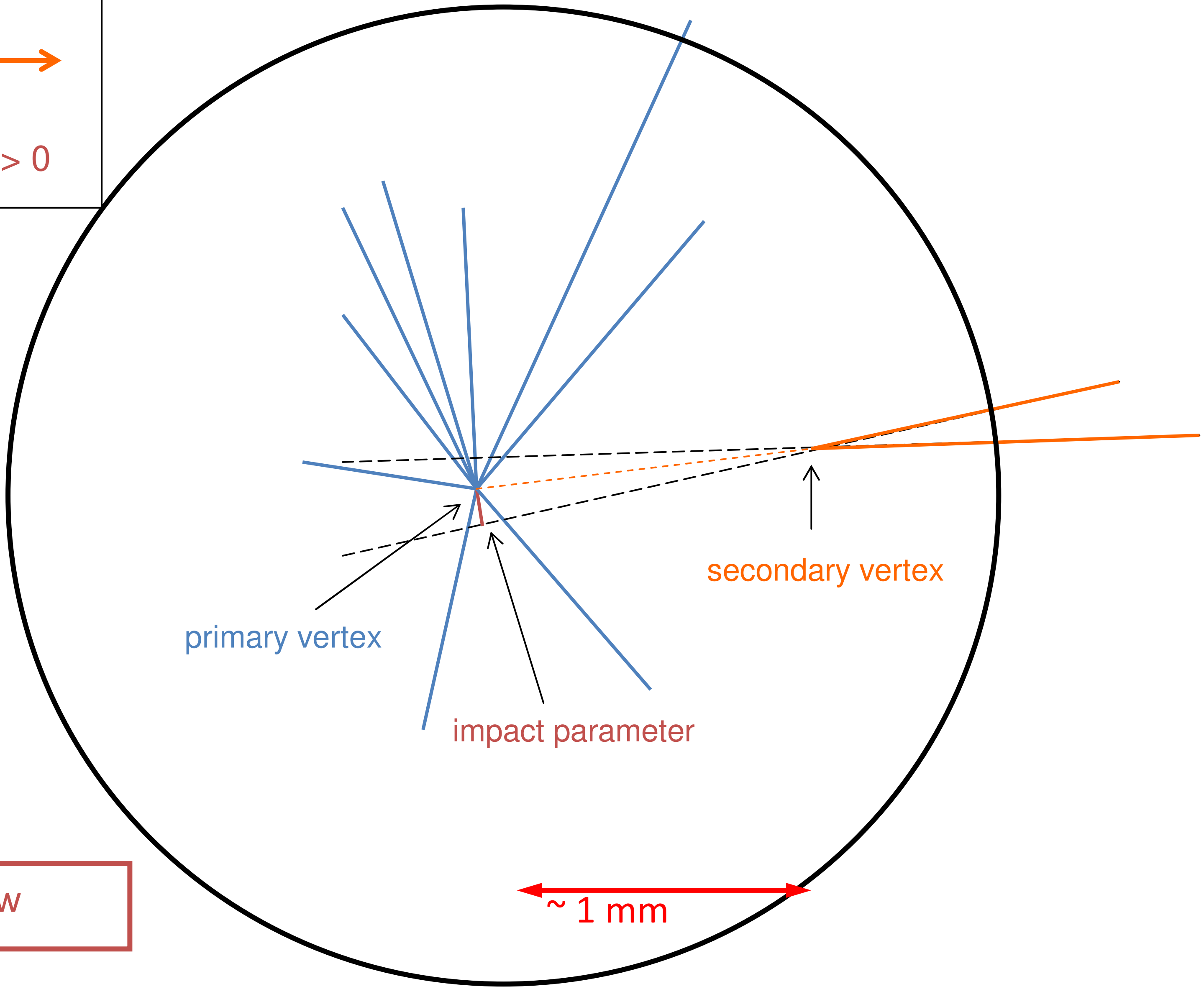
- •Tracking in mixed detector types (Si, straws, wires, GEM …)
- •Matching to other subdetectors (muons, PID, calo…)

A flexible tool to distill RAW information into decision-friendly (higher level) items



Heavy Flavor Physics with the SVT

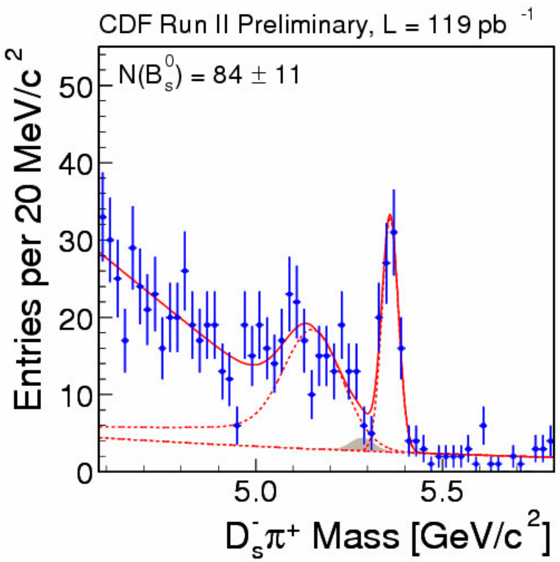




Transverse view

Heavy Flavor Physics

First-time measurement of many B_s and Λ_b Branching Fractions

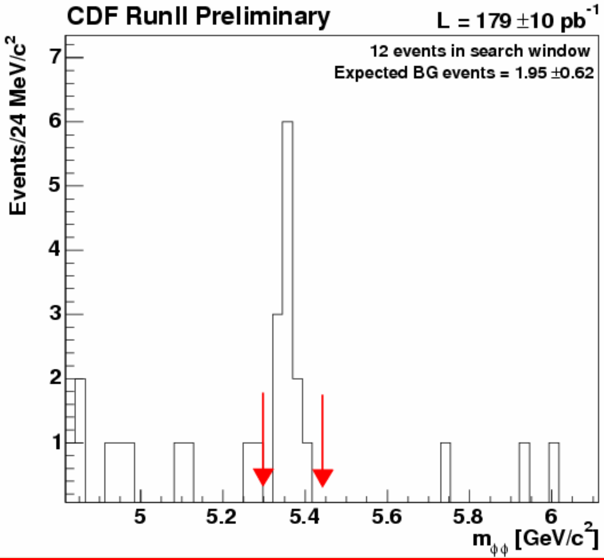


$$\frac{f_s}{f_d}\cdot\frac{Br(B_s\to D_s^-\pi^+)}{Br(B^0\to D^-\pi^+)} = 0.35\pm0.05(stat)\pm0.04(syst)\pm0.09(BR)$$

Hep-ex/0508014

$$BR(B_s\to\phi\phi) = (1.4\pm0.6(stat.)\pm0.2(syst.)\pm0.5(BR's))\cdot10^{-5}$$

Hep-ex/0502044



$$\frac{\mathrm{Br}(B_s\to\psi(2S)\phi)}{\mathrm{Br}(B_s\to J/\psi\phi)} = 0.52\pm0.13[\mathrm{stat}]\pm0.06[BR]\pm0.04[\mathrm{sys}]$$

http://www-cdf.fnal.gov/physics/new/bottom/050310.blessed-dsd/

$$\frac{Br(B^0\to D_s^+D^-)}{Br(B^0\to D^-3\pi)} = 2.00\pm0.16(NC)\pm0.12(syst)\pm0.50(BR)$$

http://www-cdf.fnal.gov/physics/new/bottom/050310.blessed-dsd/

$$\frac{BR(\Lambda_b\to\Lambda_c^+\pi^-)}{BR(\bar{B}^0\to D^+\pi^-)} = 3.3\pm0.3\ (\mathrm{stat})\pm0.4\ (\mathrm{syst})\pm1.1\ (\mathrm{BR+FR})$$

Hep-ex/0601003

$$\frac{\mathcal{B}(\Lambda_b\to\Lambda_c^+\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b\to\Lambda_c^+\pi^-)} = 20.0\ \pm3.0\ (stat)\pm1.2\ (syst)\begin{array}{c}+0.7\\-2.1\end{array}(BR)\pm0.5\ (UBR)$$

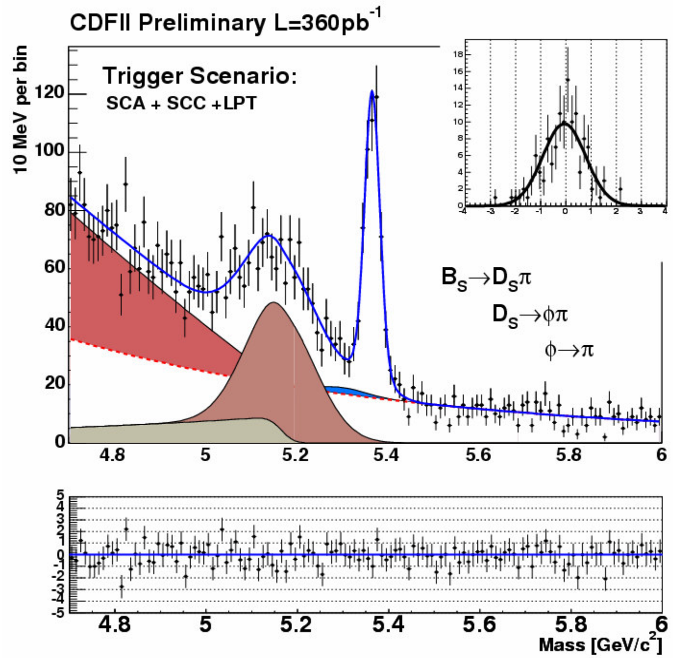
http://www-cdf.fnal.gov/physics/new/bottom/050407.blessed-lbbr/lbrBR_cdfpublic.ps

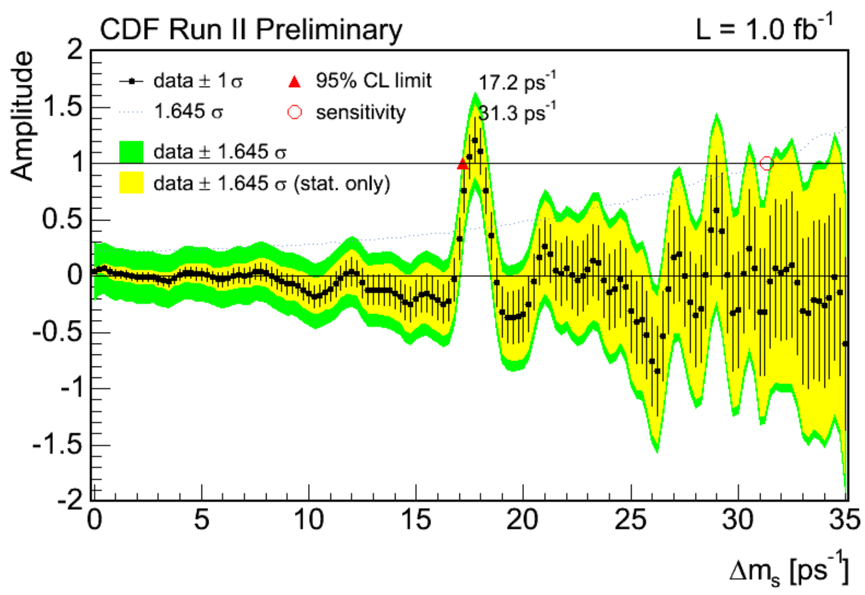
Heavy Flavor Physics

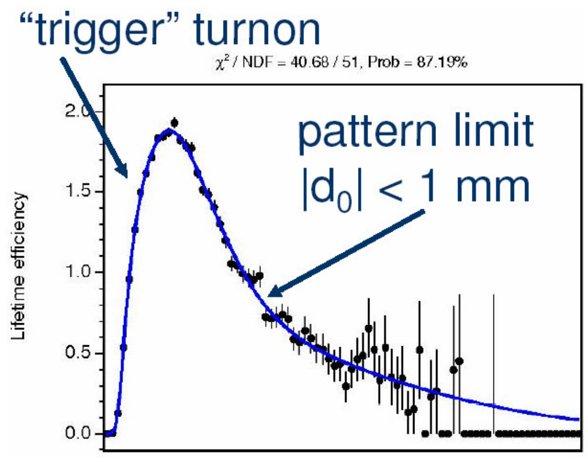
$\tau(B^+)$ = **1.661±0.027±0.013 ps**
$\tau(B^0)$ = **1.511±0.023±0.013 ps**
$\tau(B_s)$ = **1.598±0.097±0.017 ps**

Control measurements

<30% due to trigger efficiency







These results would not have been possible without the SVT!

New Physics: LHC

$Z^0 \rightarrow bb$ Calibration sample

bbH/A → bbbb

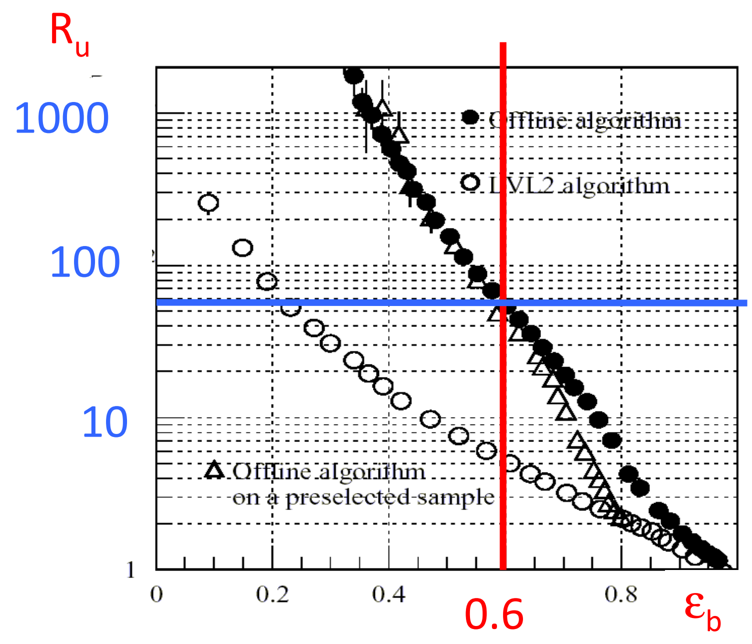
ttqqqq-bb

ttHqqqq-bbbb

H/A ttqqqq-bb

Hhhbbbb

H^{+-} tbqqbb

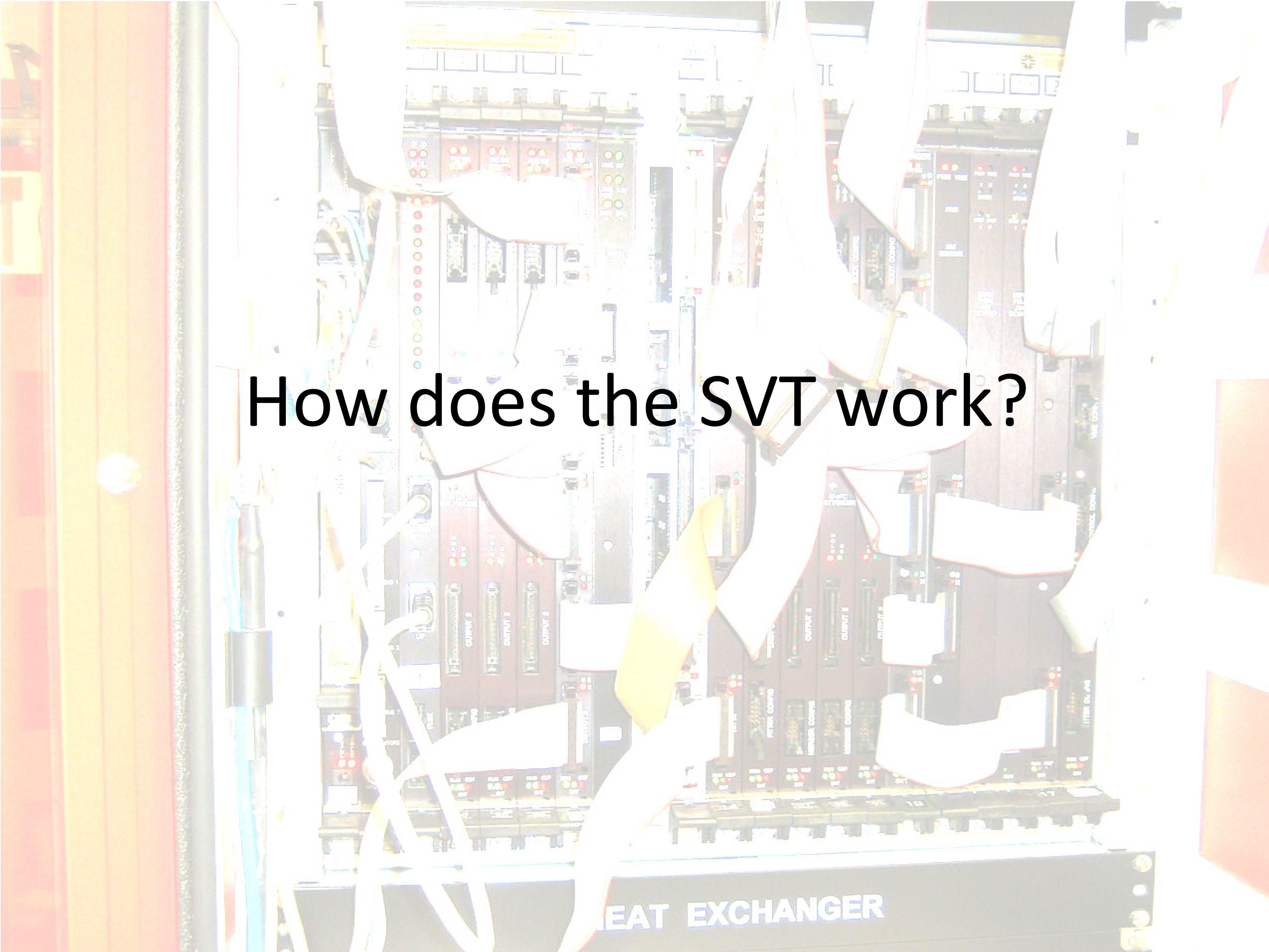


ATLAS TDR-016

Fast-Track brings offline b-tag performances early in LVL2

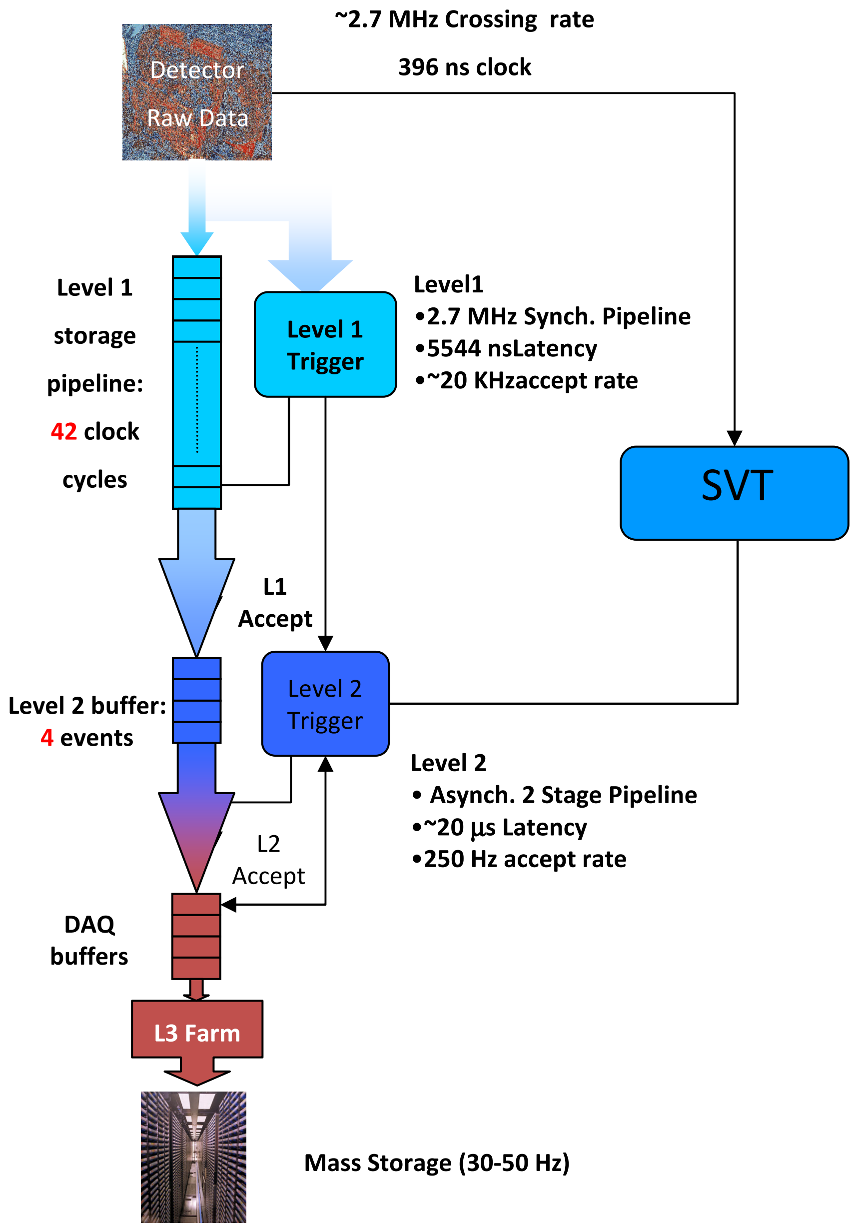
You can do things 1 order of magnitude better

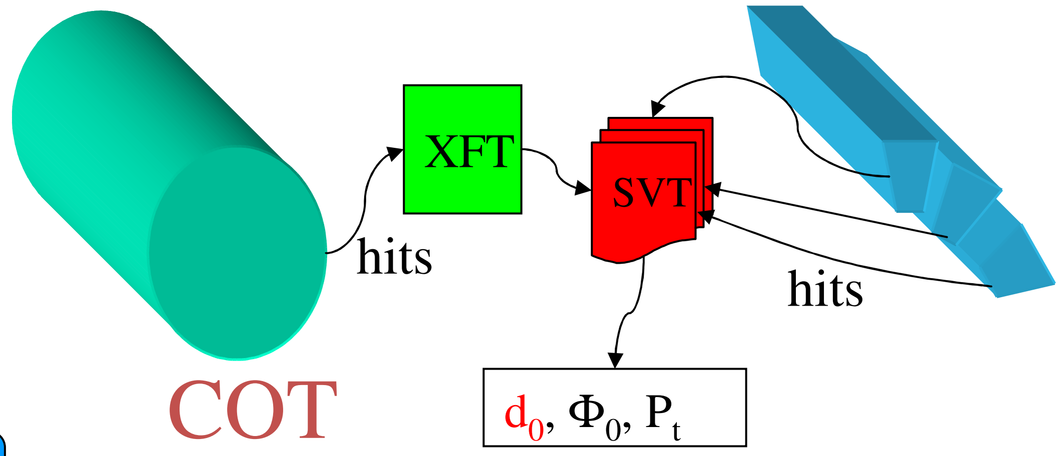
How does the SVT work?



SVT within the CDF DAQ

The CDF Trigger





Goals:

- Offline-like track parameters (IP in particular)
- In Real time, as early as possible within DAQ constraints

Keys to sufficient speed and accuracy:

- Combine L1 COT "tracks" (Pt,Φ) with Silicon detector information
- Drop stereo information
- Parallelize tasks in hardware

The SVT Algorithm

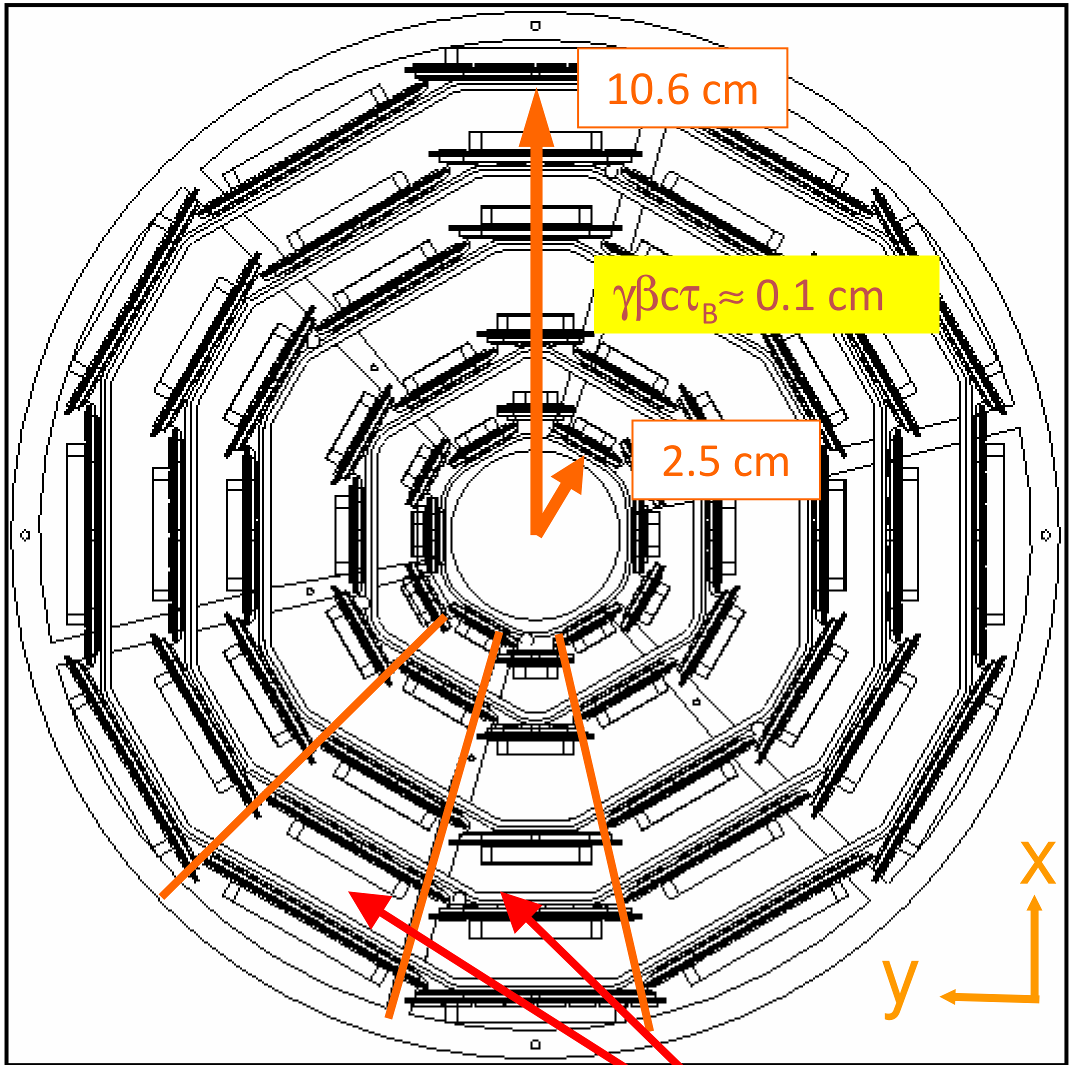
How do we measure tracks in ~20 μs/event, when software takes typically ~1s?

Naively going through the combinatorial for N hits on M layers: ~N^M, optimizing we can make this almost linear!

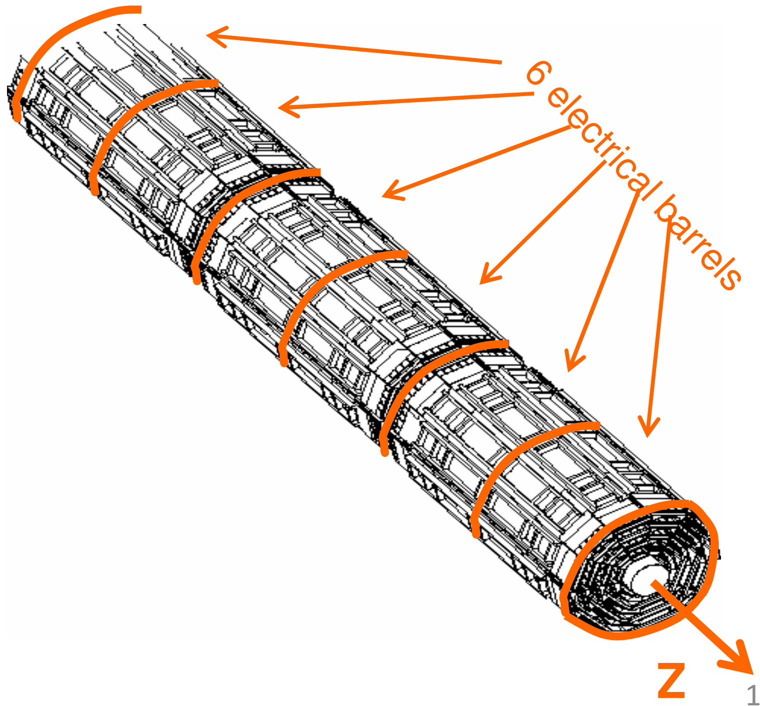
- (1) Do everything you can in parallel and in a pipeline
- (2) Streamlined pattern recognition
  - Bin coordinate information coarsely into roads
  - Examine all possible patterns in parallel (of course)
  - This is done in a custom chip
- (3) Linearize the fitting problem
  - i.e. solvable with matrix arithmetic

The wisest are the most annoyed by the loss of time. -Dante

(1) Symmetry & Parallelism



Symmetric, modular geometry of silicon vertex detector lends itself to parallel processing



Note “wedge” symmetry

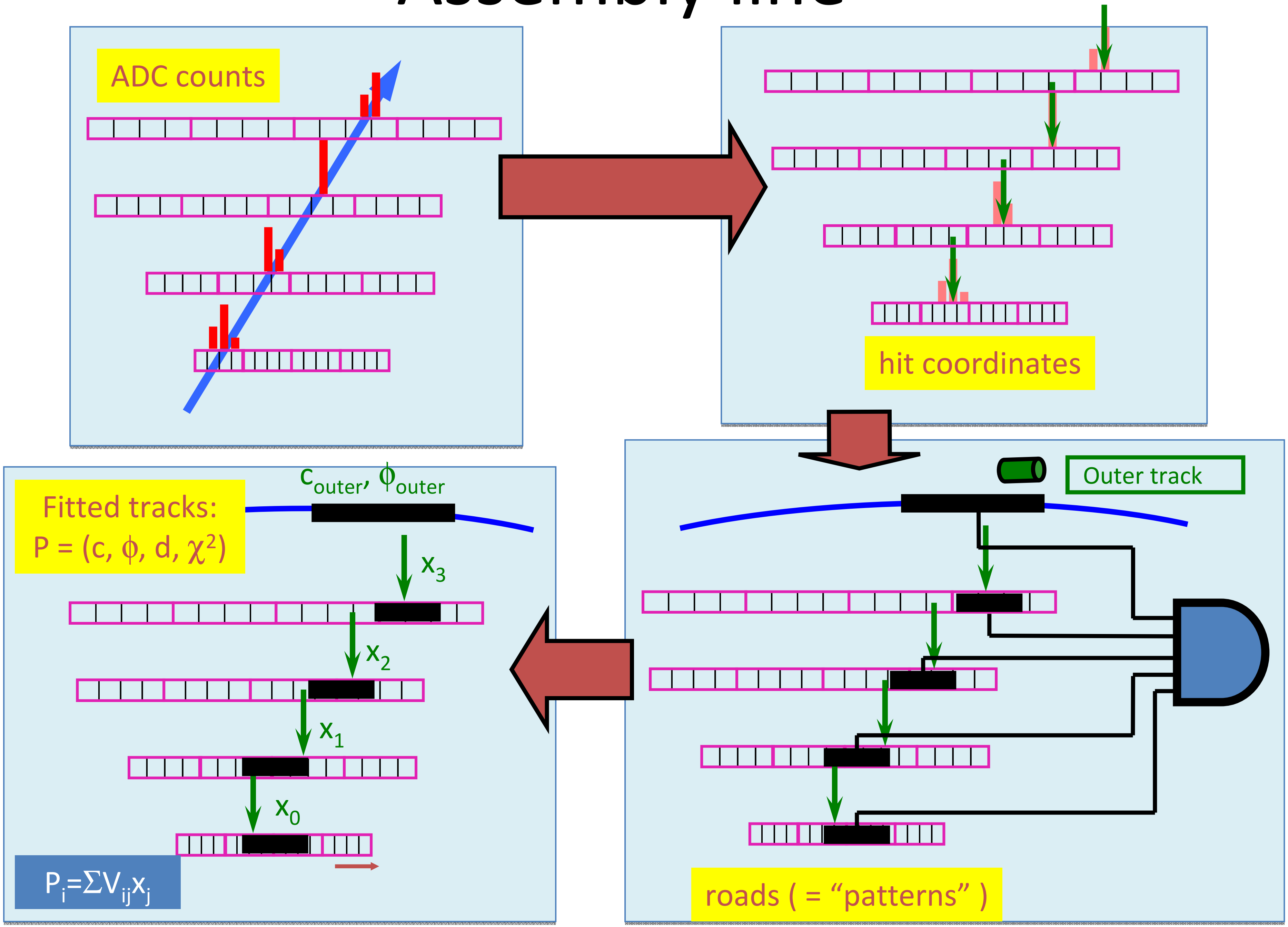
SVT data volume requires parallelism

2 meters

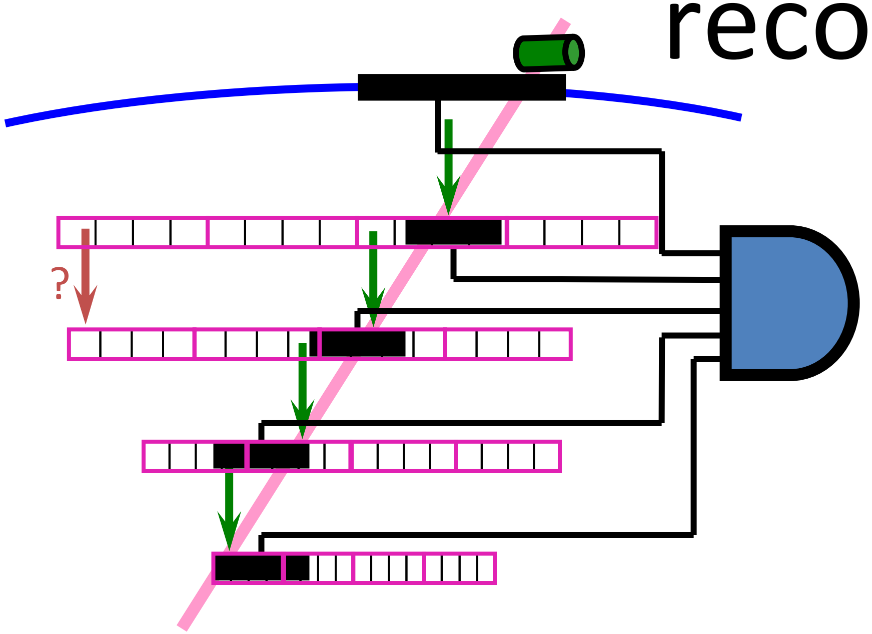
Reduces gigabytes/second to megabytes/second

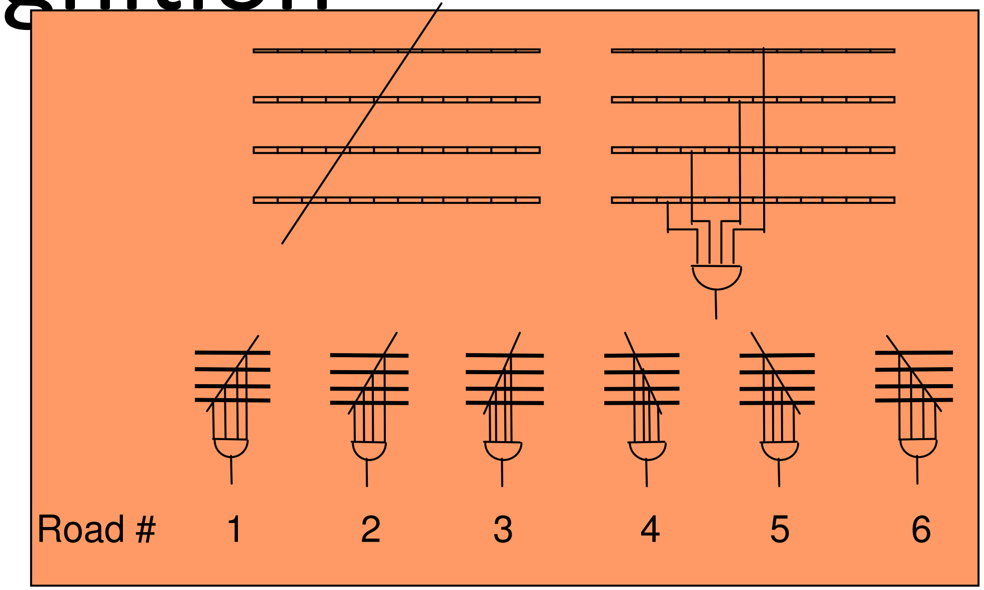
Peak (avg): 20 (0.5) GB/s → 100 (1.5) MB/s

“Assembly line”



(2) Streamlined pattern recognition





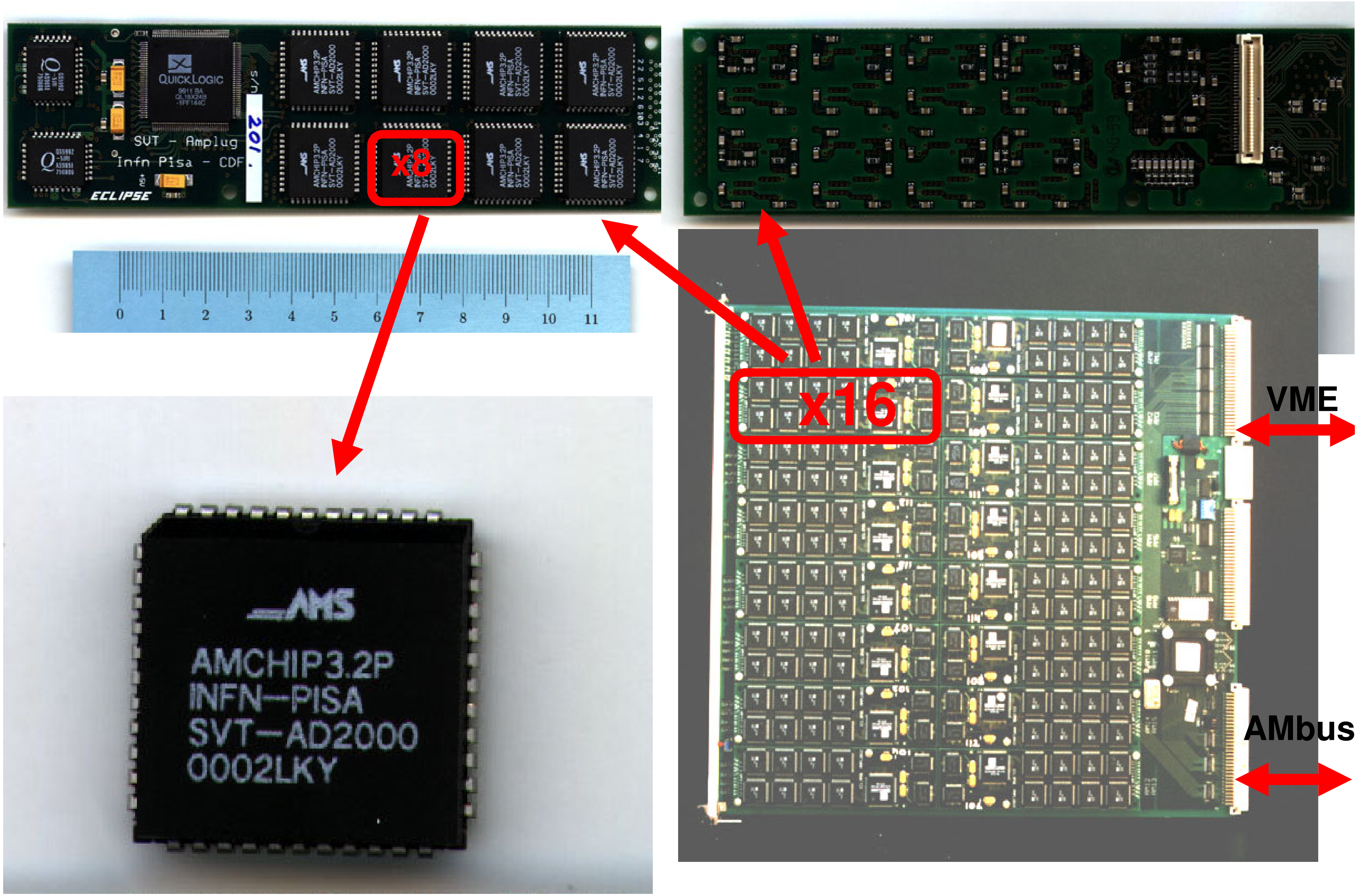
The way we find tracks is a cross between

- ➢ searching predefined roads
- ➢ playing BINGO

B	I	N	G	O
2	17	35	48	61
10	21	39	53	66
14	20	free	55	65
8	25	41	52	62
6	16	37	46	67

Time ~ $A*N_{hits} + B*N_{matchedroads}$

Associative memories: Our Bingo Cards



How many “bingo cards” do we need?

Two main parameters affect this:

•Track finding efficiency

•Pattern occupancy

•Coarser detector binning:

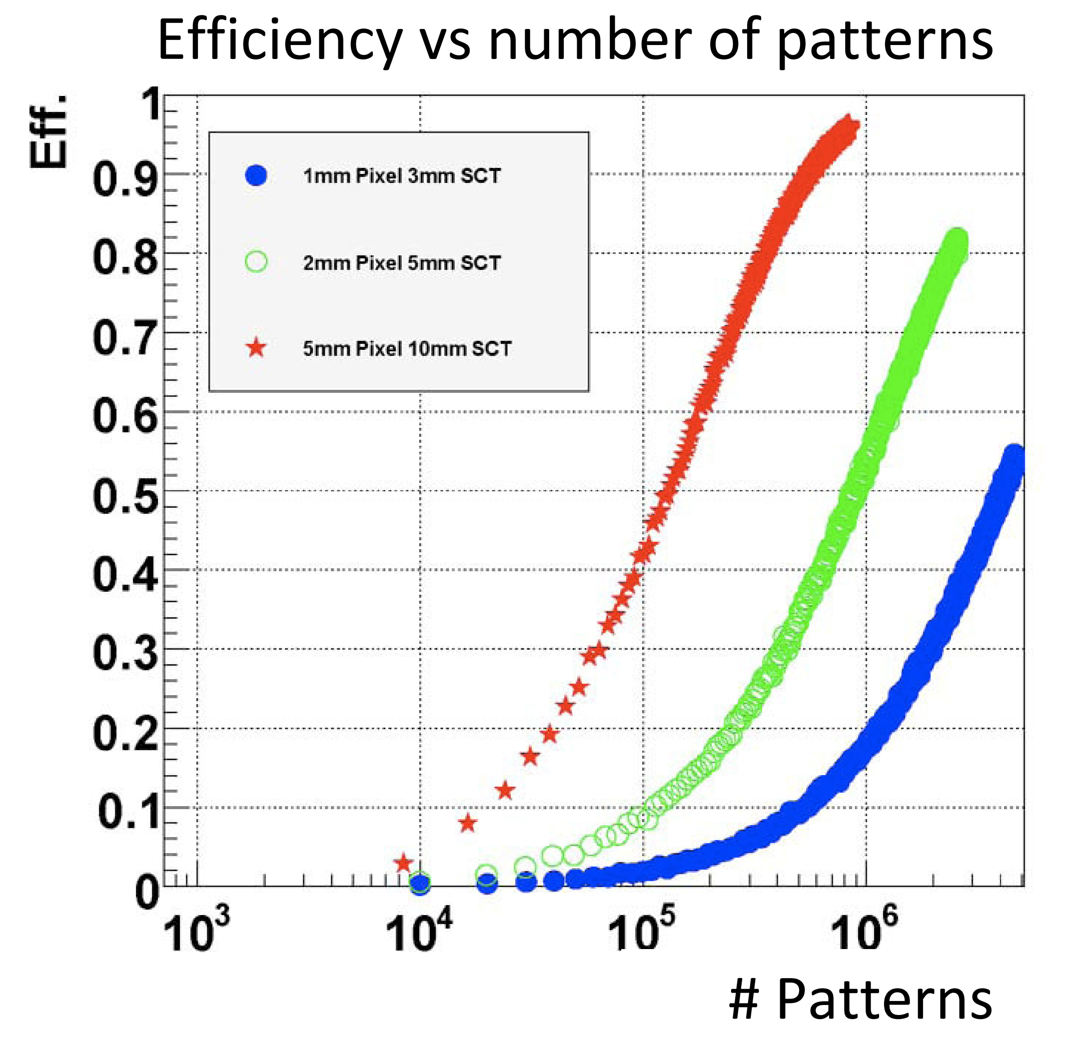
•Less patterns for the same efficiency

•More occupancy perpattern

•A compromise needs to be found based on the specific application

•CDFII: 32k (➔512k)/wedge

An example from the ATLAS /FTK proposals:



(3) Linearization

6 coordinates: x_1, x_2, x_3, x_4, x_5 (P_T), x_6 (ϕ)

3 parameters to fit: P_T , ϕ , d

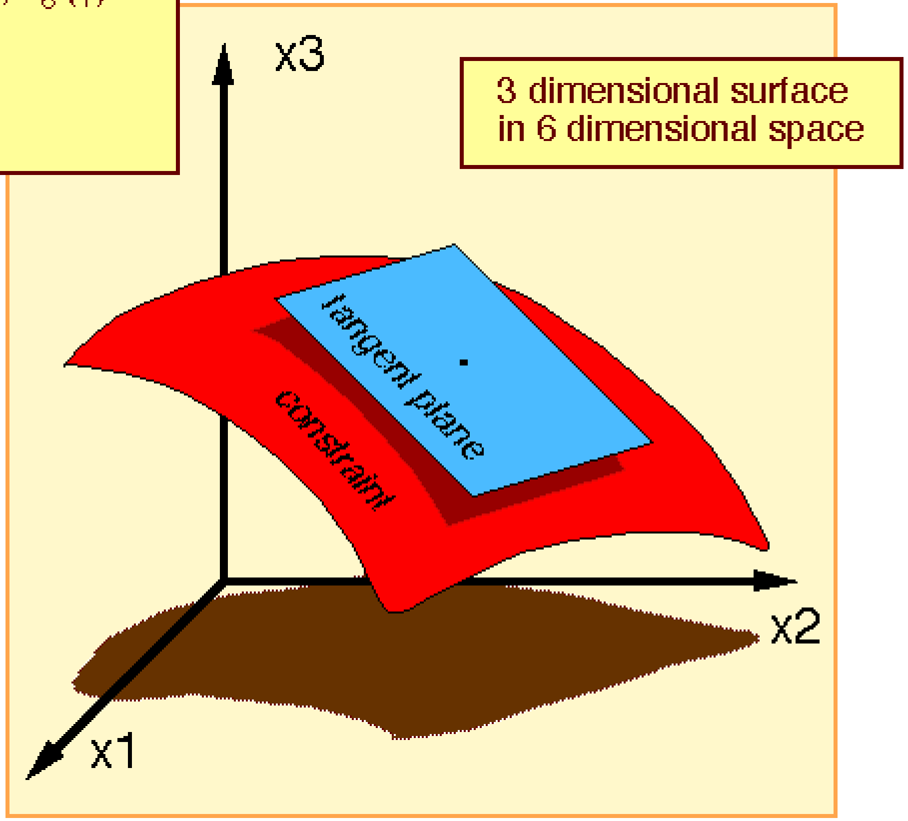
3 constraints

tangent plane:

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

track parameters:

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



Linear approximation is so good that a single set of constants is sufficient for a whole detector wedge (30° in ϕ)

How good is Linearization?

For a circle tangent to the x axis,

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

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

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

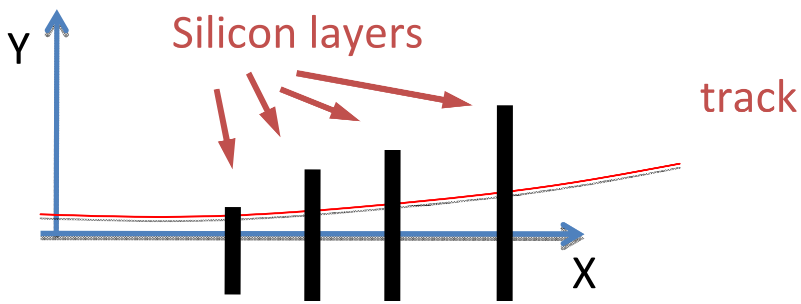
Silicon: constant x, not constant r:

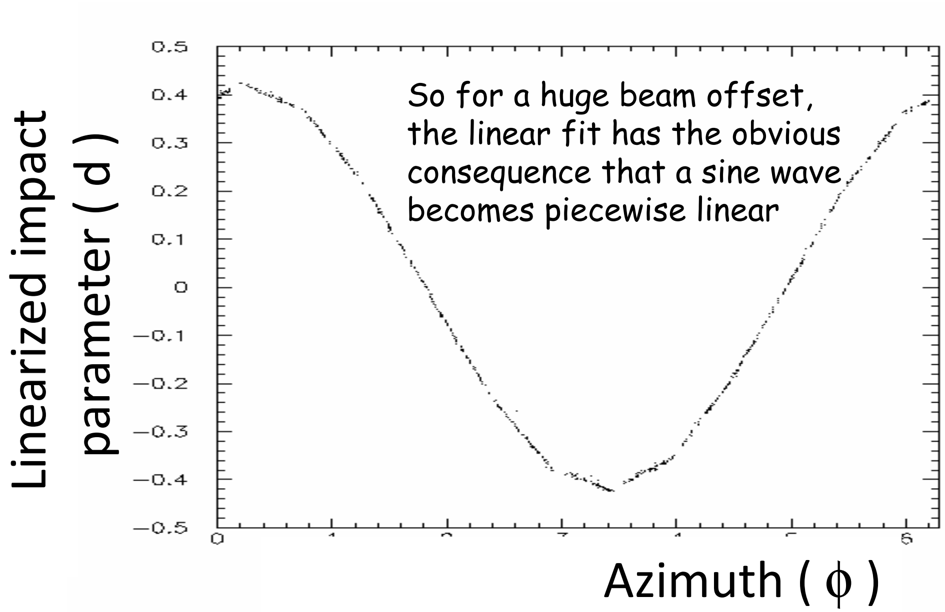
$$y = \boxed{\frac{c}{\cos^3\phi}} x^2 + x \boxed{\tan\phi} + \boxed{\frac{d}{\cos\phi}}.$$

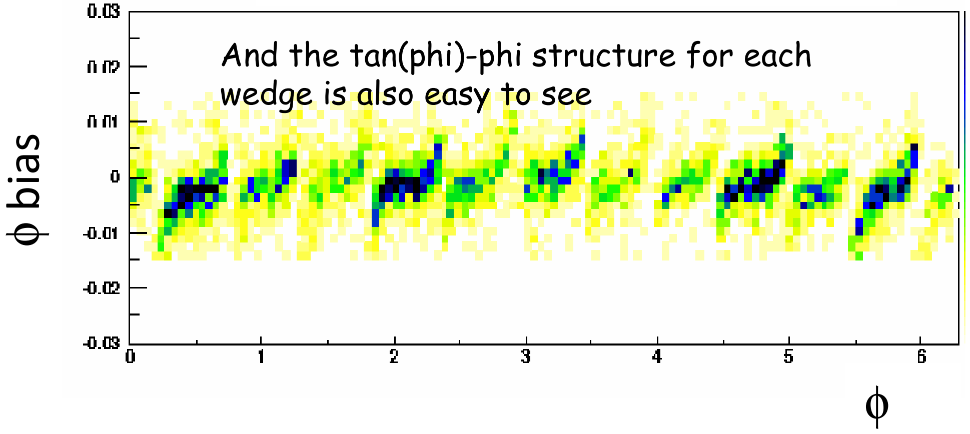
$\Rightarrow$

(1) Fit is linear in $\tan(\phi)$, not ϕ

(2) up to 3.5% scale error on d: 3.5 μm at 100 μm (at 15°)





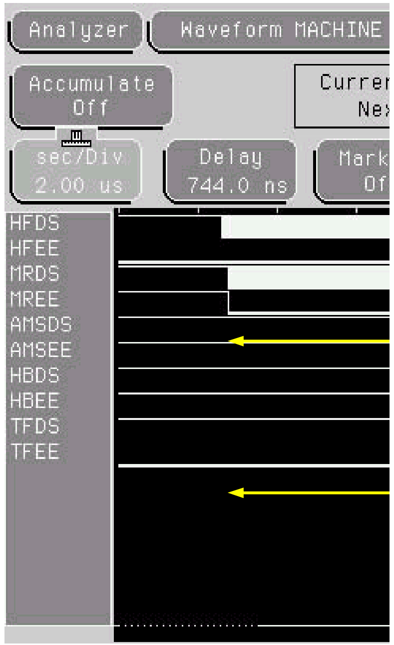


SVT Deployment

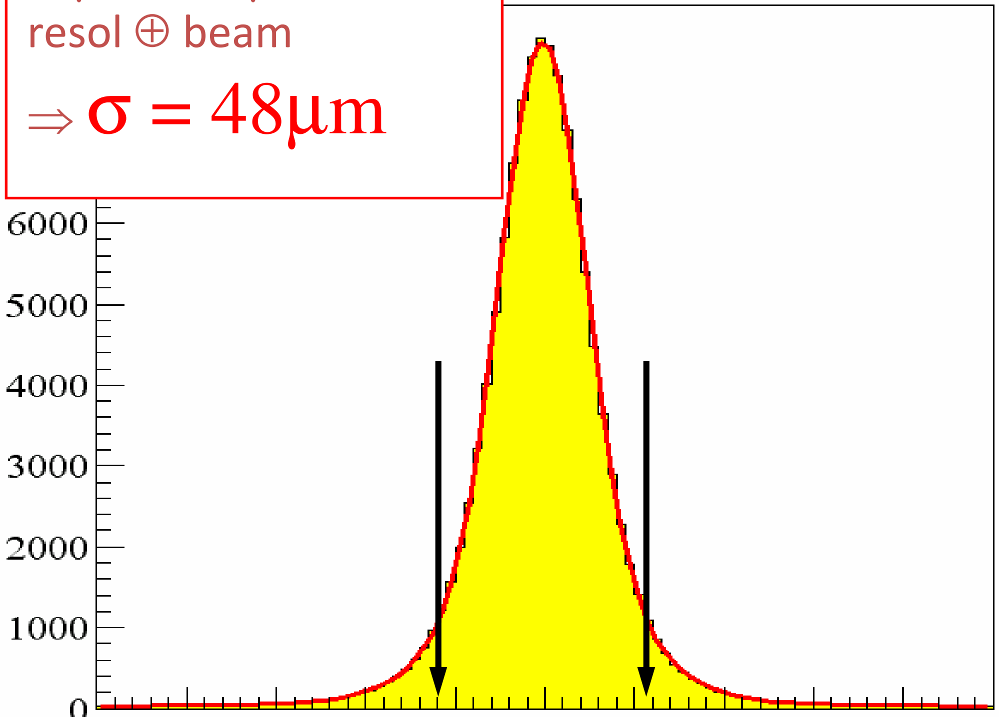
Some features enormously simplified the SVT installation:

- Modularity (e.g. uniform standard in data paths)
- Intrinsic diagnostic tools: each input, and critical registers are VME-accessible without affecting dataflow
- Detailed emulation of the hardware: we can reproduce the SVT output in the CDF analysis framework with discrepancies $<10^{-5}$

Success!



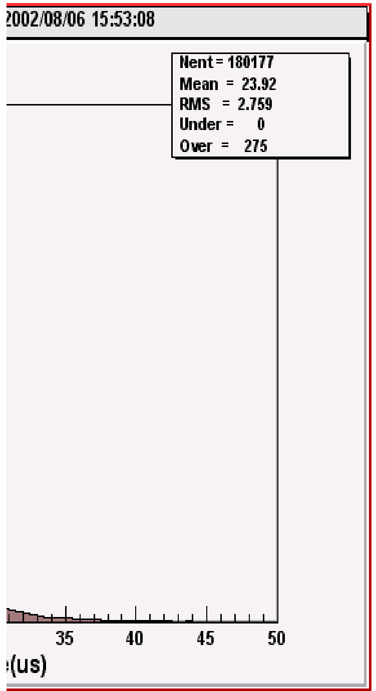
35µm ⊕ 33µm
resol ⊕ beam
⇒ σ = 48µm



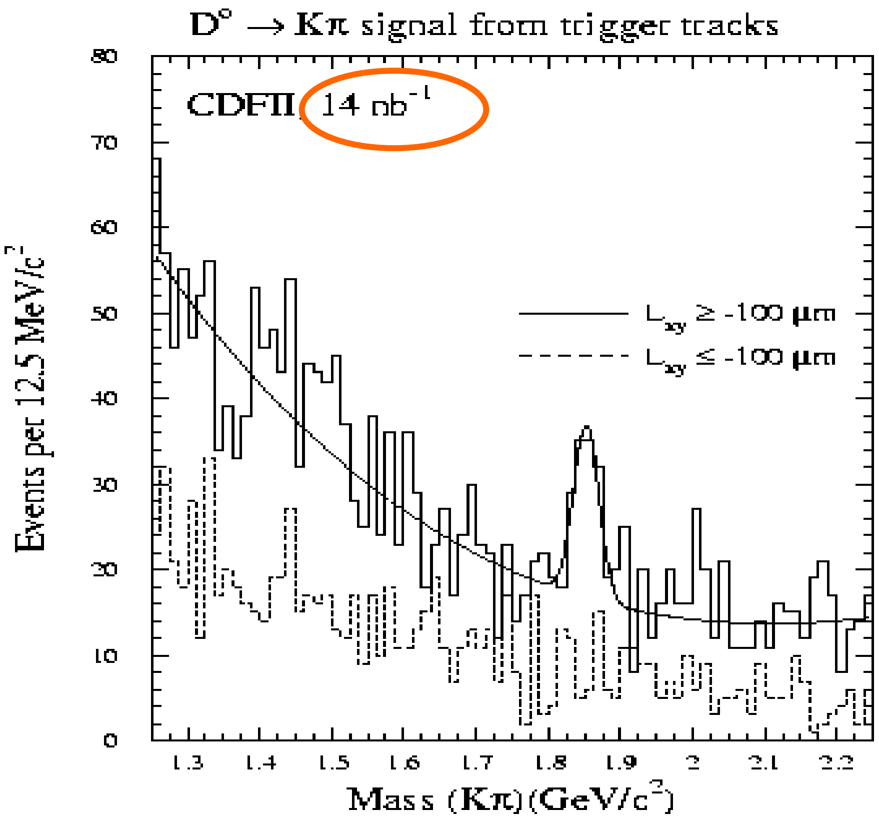
-500 -250 0 250 500

silicon trigger impact parameter (µm)

24 µs
Level 1 accept
to SVT done

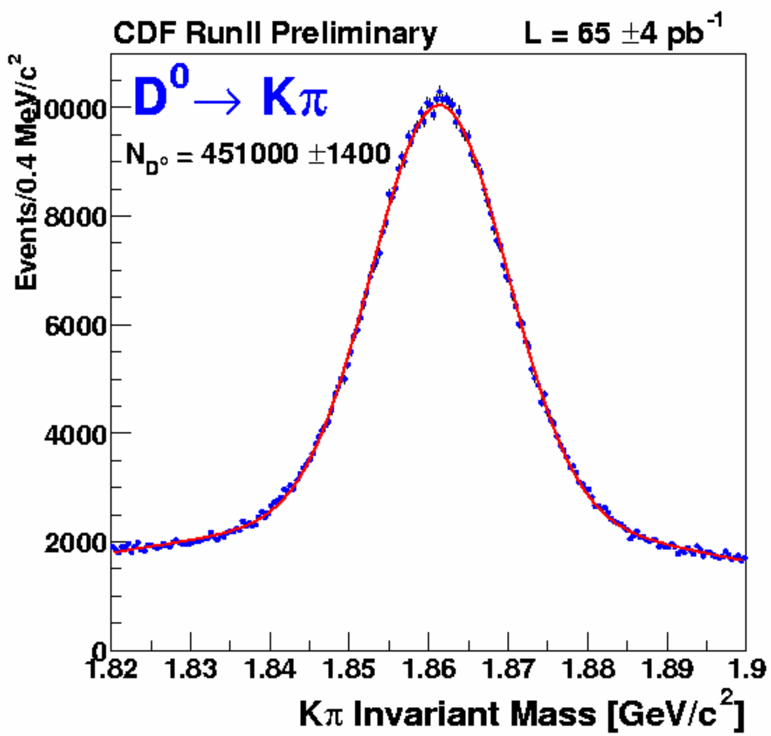


Physics!



October 2001 test runs
(~3 minutes at design luminosity)

TeVatron turned out to be a pretty clean, high-yield charm factory!

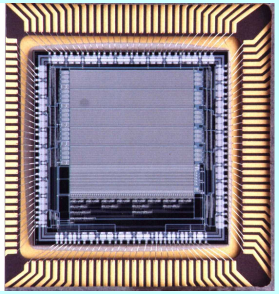


Improvements & Upgrades

Scaling to LHC-class complexity

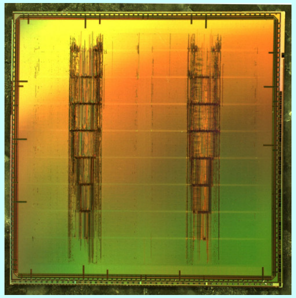
- Not easy:
  - 500K channels → O(100M)
  - 20μs→2μs
  - O(10^7) patterns needed
- But feasible:
  - SVT has been designed in ~1990 with (at the time) state of the art technology
  - We have been thinking a lot on how to improve the technology
  - The SVT 'upgrade' (2005) is in fact partly done with hardware capable of LHC-class performance!

1998: Full custom VLSI "Associative Memory" chip:



128 patterns

2004: Standard Cell "Associative Memory" chip:



~5000 patterns

Beyond track parameters

- The SVT architecture is extremely modular
- With little interfacing, any detector can in principle be used as reconstruction seed:
  – Muon detectors
  – Calorimetry
  – …
- What possibilities does this open at trigger level?
- Further abstraction level: use multiple layers of pattern recognition hardware
  - “Successive approximation” pattern recognition
  - Pattern recognition beyond tracks:
  – Vertices?
  – Topological triggers?

Conclusions

- SVT provides a very powerful real-time general-purpose "funnel"
  - Can handle mixed detectors
  - Pattern recognition core can be used in an hierarchical fashion to derive objects of increased complexity
- Critical design parameters:
  - Detector:
    - Geometry
    - Segmentation
    - Readout characteristics
  - Environment:
    - Occupancy
    - Physics case