the History of the CDF Silicon Vertex Trigger

Luciano Ristori

June 10, 2011

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- a success story: how did it happen
- some important design choices
- what did we learn
- final remarks

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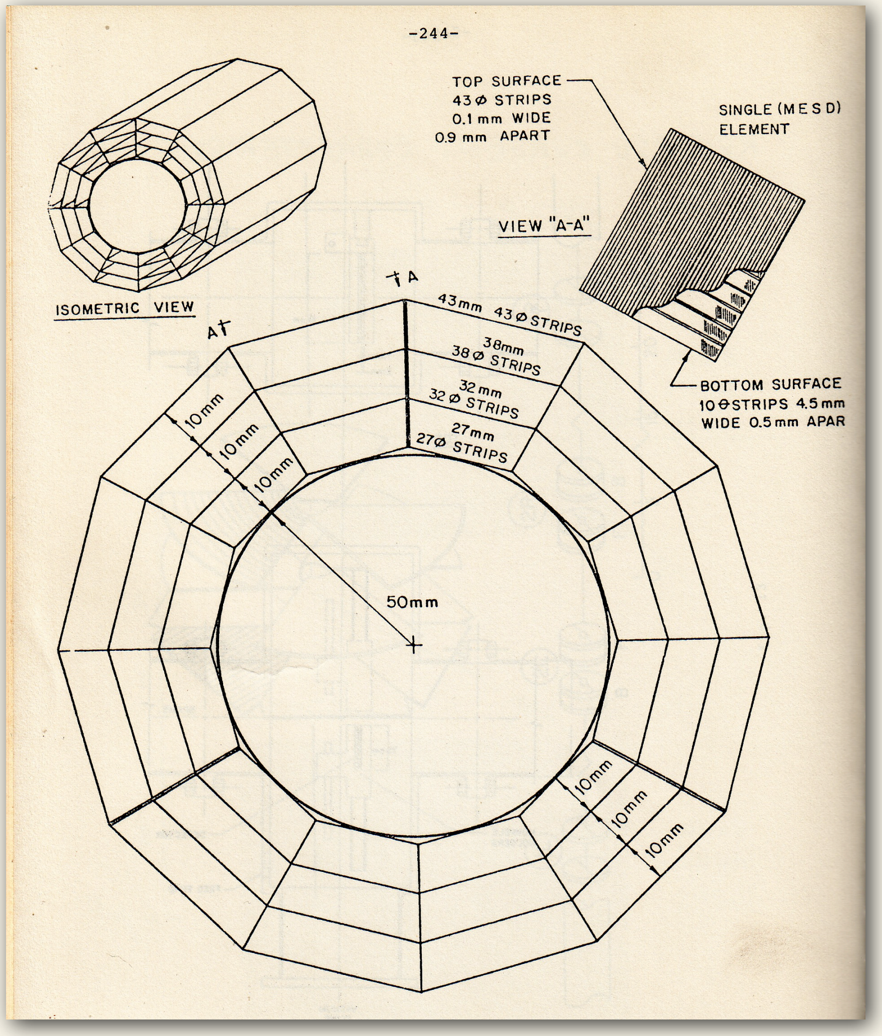
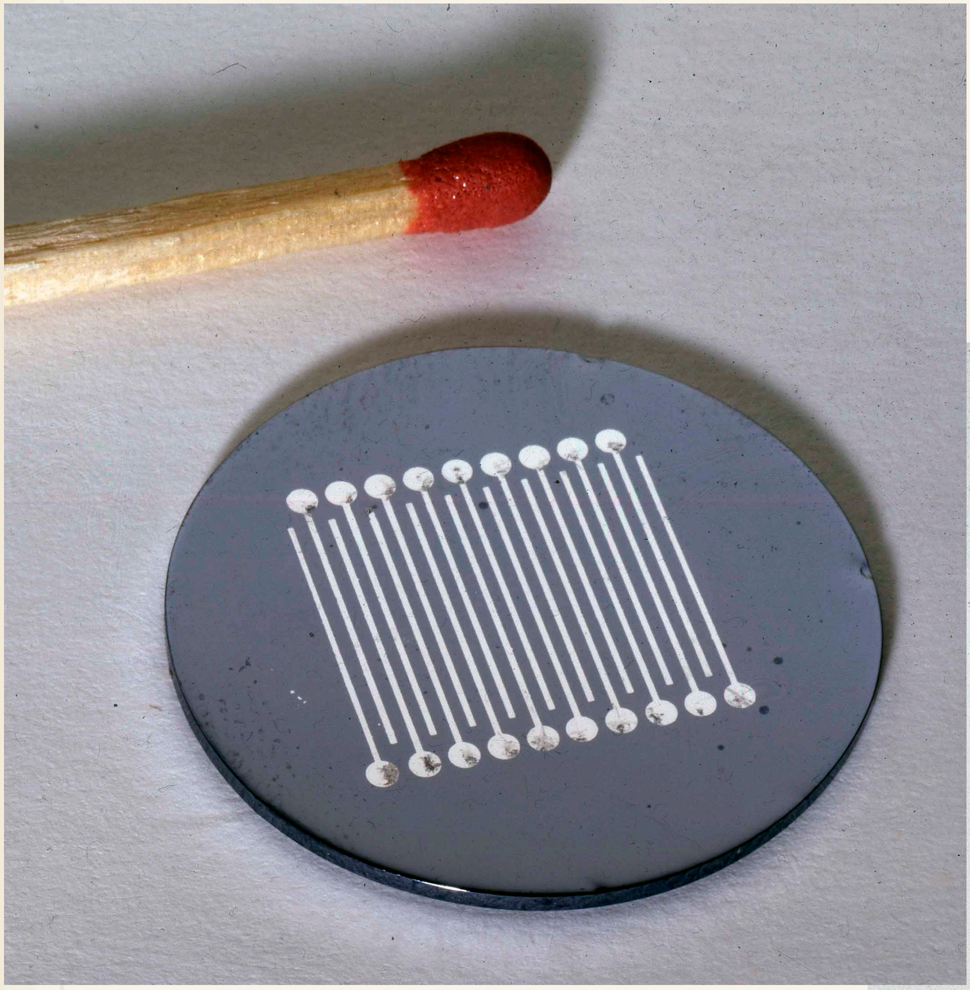
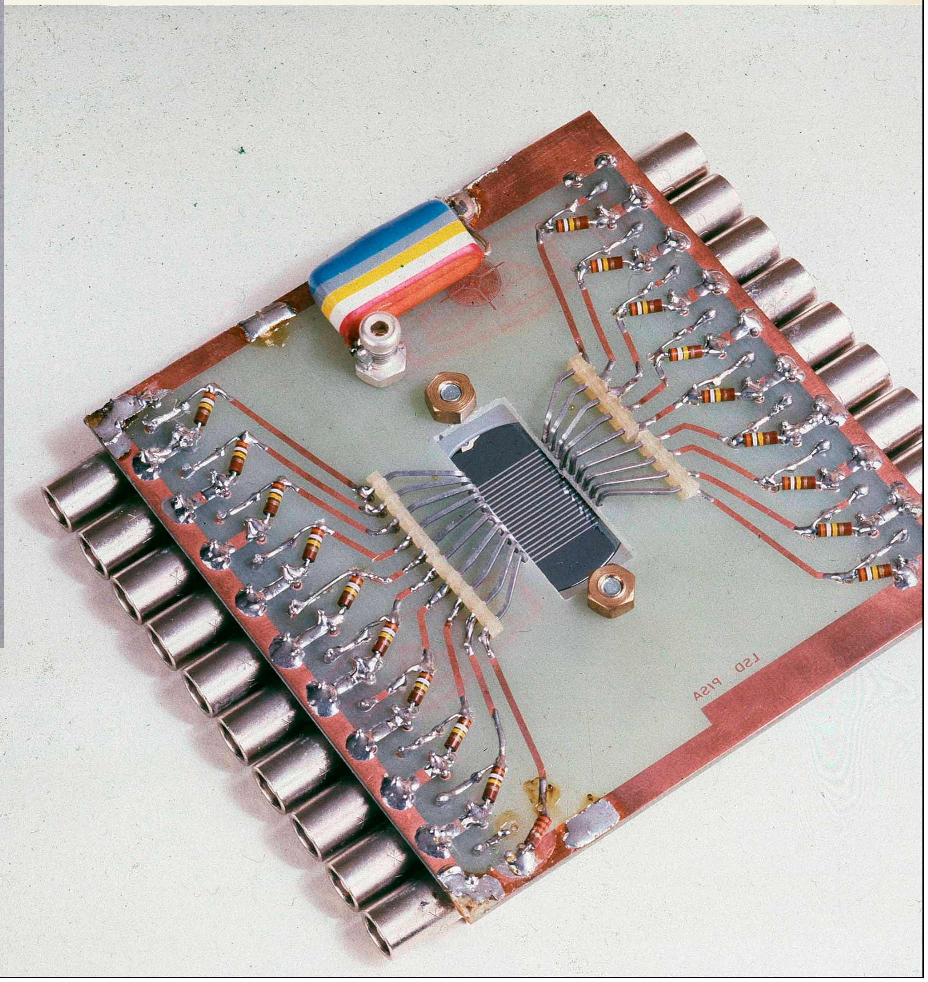


1981: the first conceptual design of a *silicon vertex detector* for a collider experiment

from the
“CDF Technical Design Report”
1981

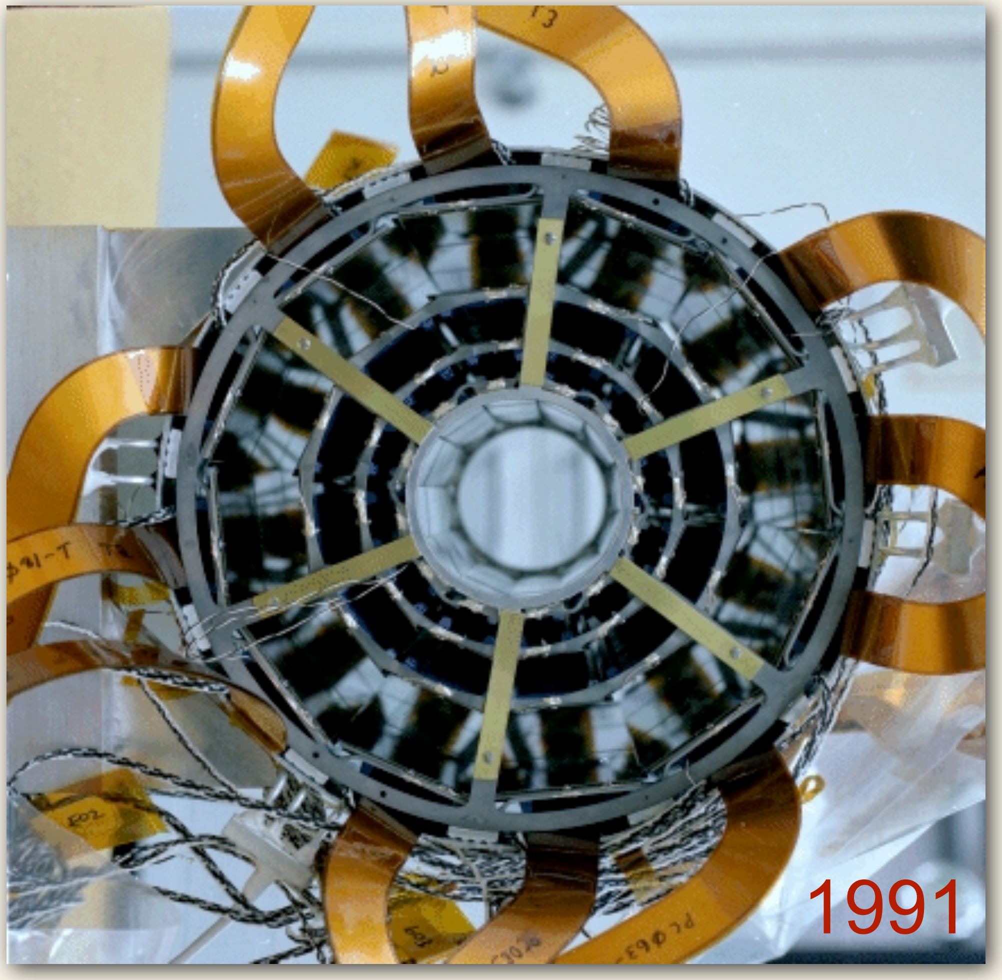


some early prototypes of microstrip silicon detectors



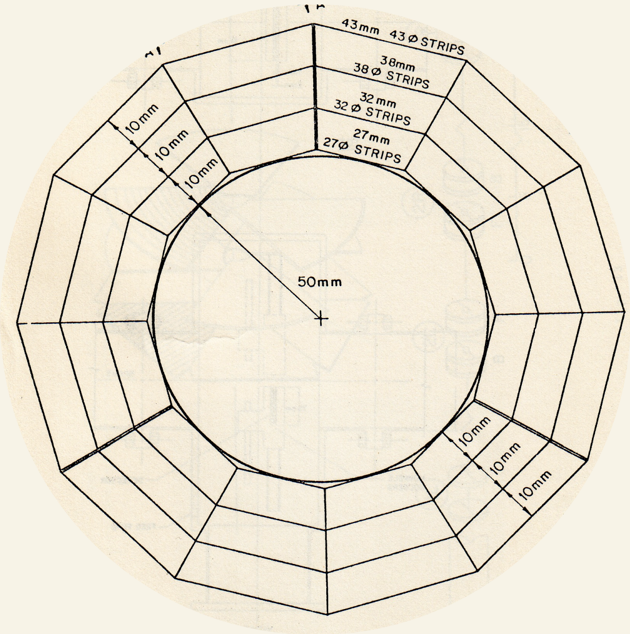
SVX: the first CDF micro vertex detector

finished in 1991

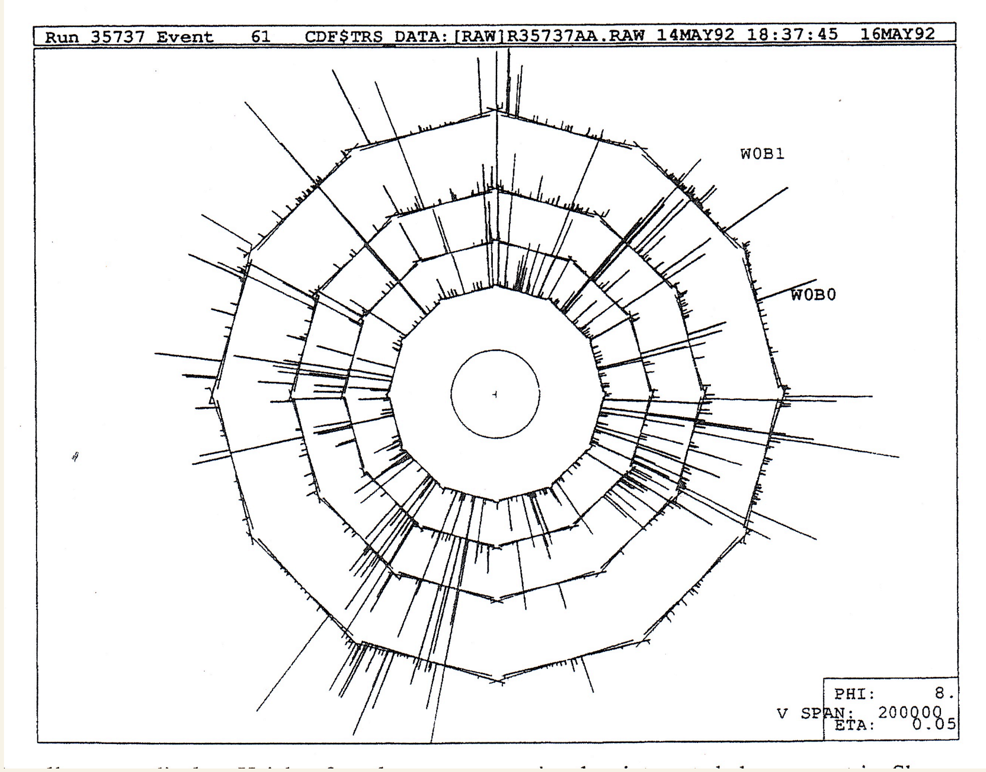


1991

1981



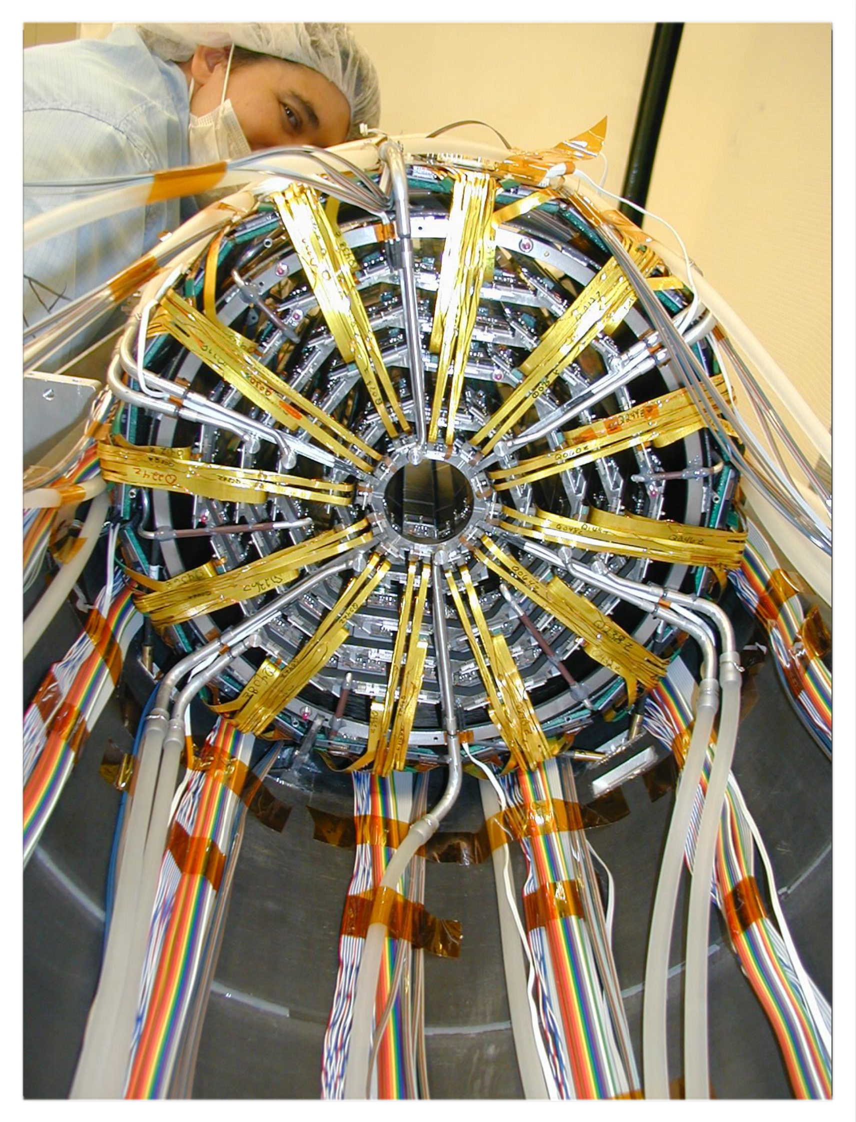
1992: particles from collisions are recorded by SVX

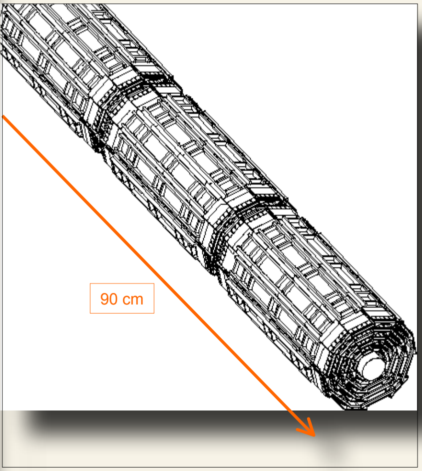


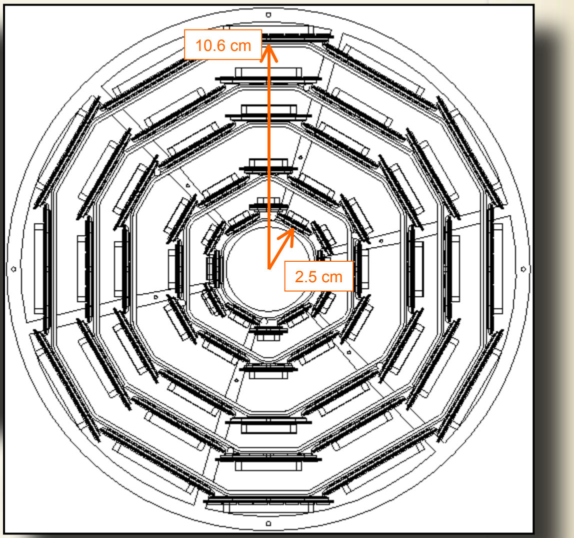
will be of crucial importance for the discovery of the Top quark in 1995

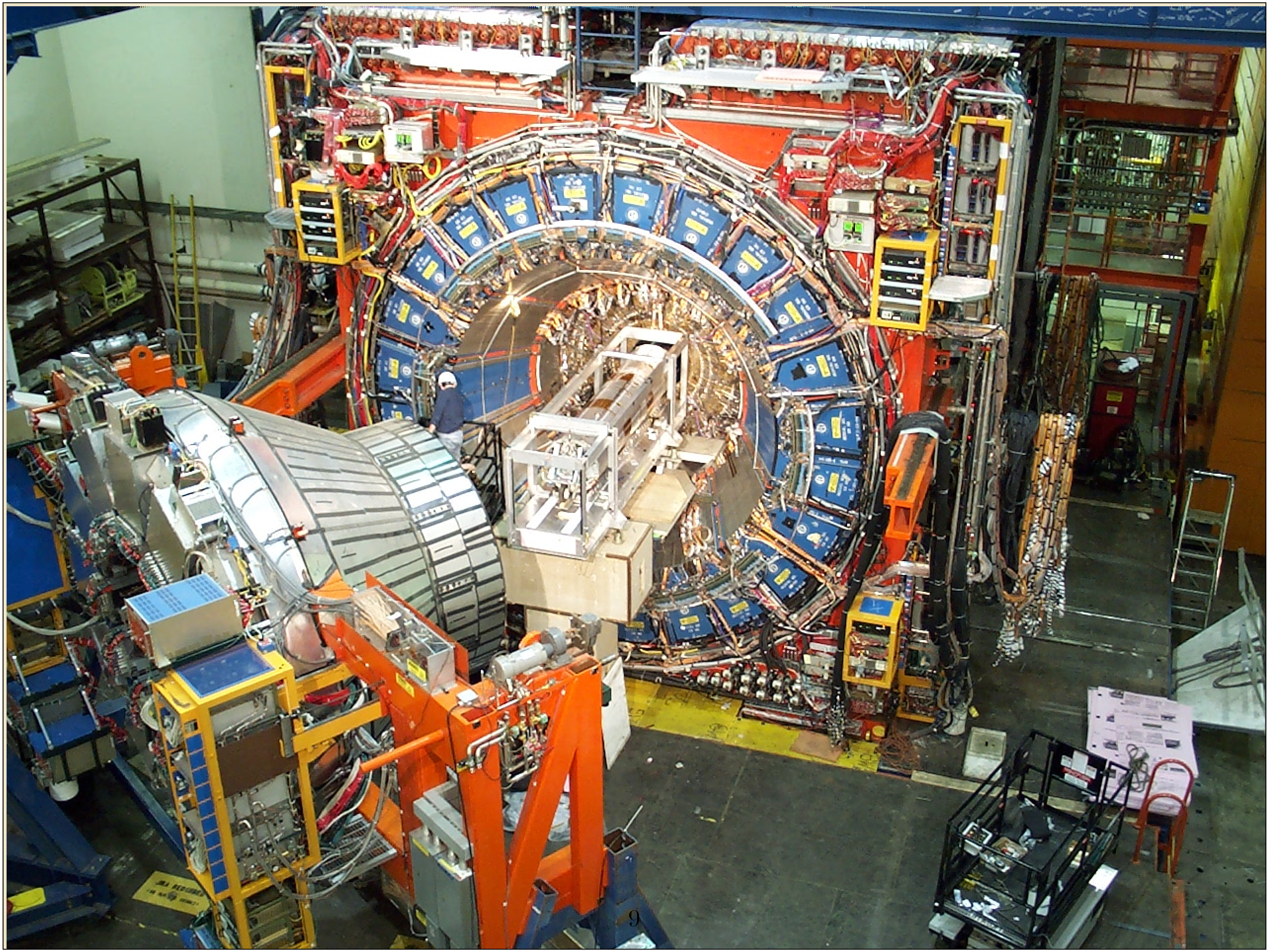
SVX II: the latest CDF micro vertex detector

commissioned in 2001



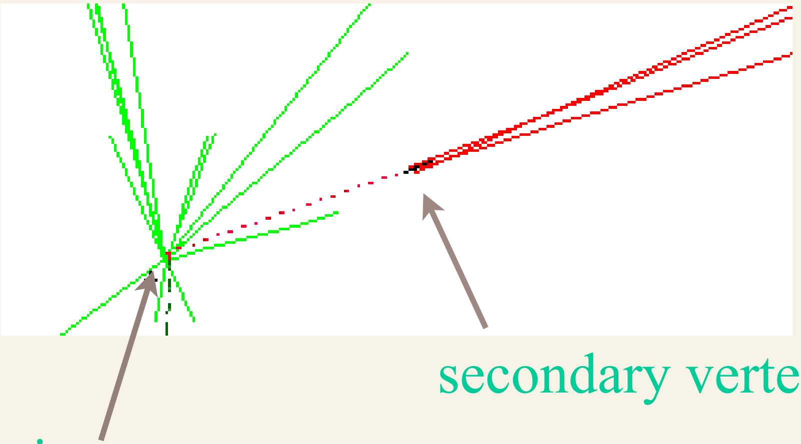






Heavy Flavor Physics

- at the start of CDF, at the end of the ‘80s, the first priority was the search for the *Top* quark but...
- quarks with *Charm* and *Beauty* are produced abundantly at the Tevatron and turn out to be extremely interesting too, but they are hard to identify being produced mostly at relatively low transverse momentum
- their main characteristics is a relatively long lifetime which creates *secondary vertices* at distances of the order of millimeters from the collision point

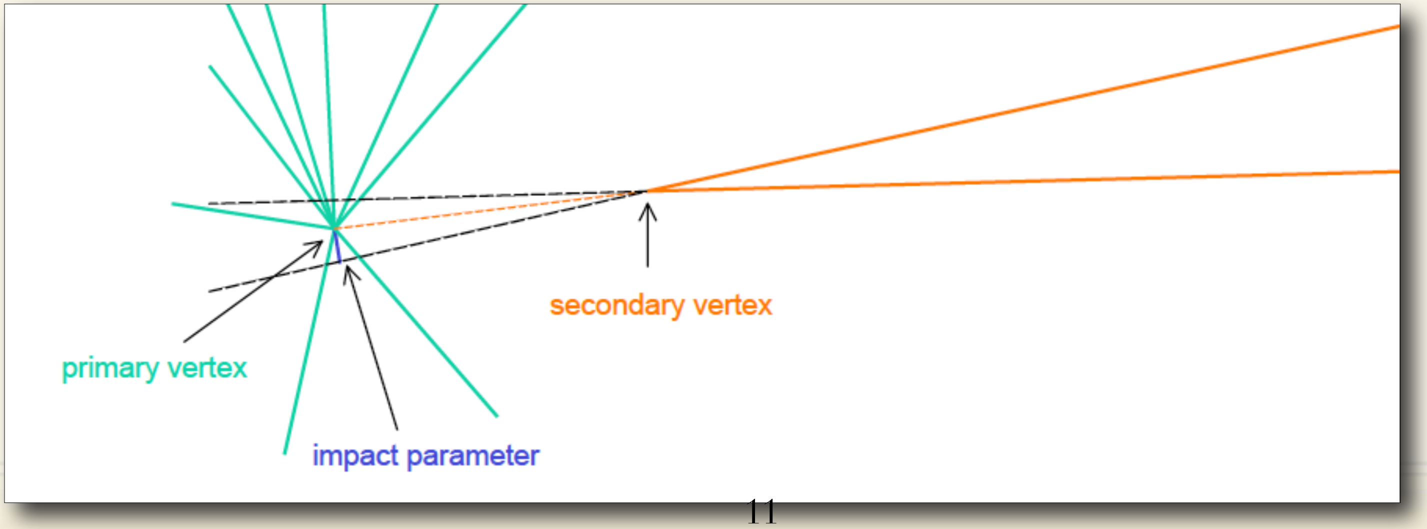


secondary vertex

primary vertex

to trigger on secondary vertices you need to

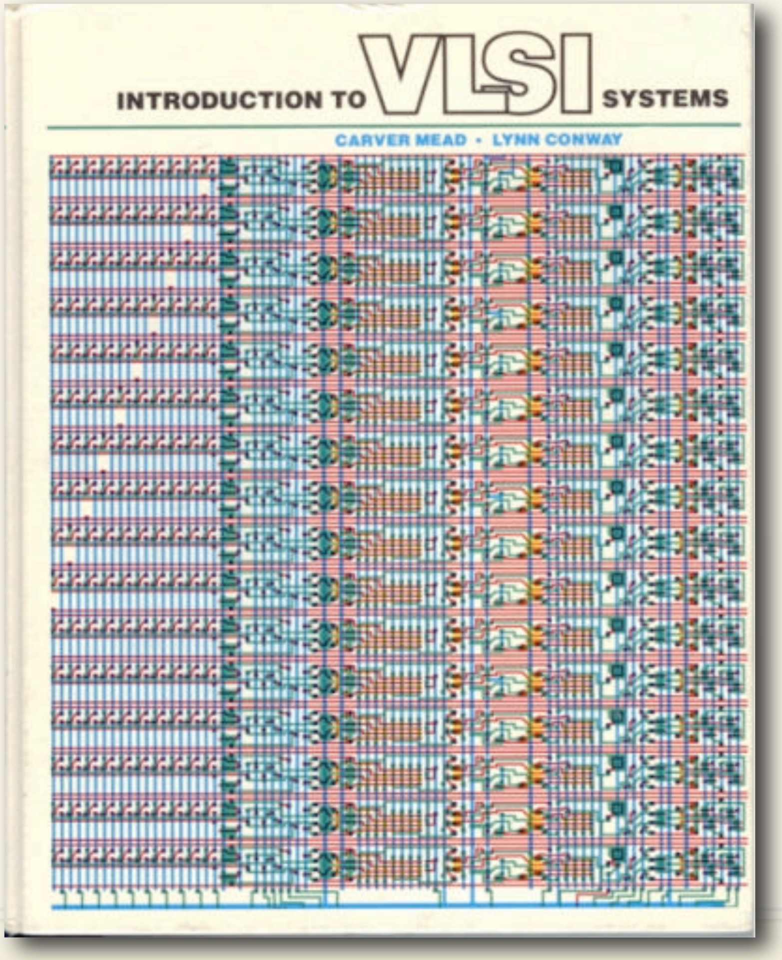
- perform pattern recognition and sort hits into tracks
- fit all tracks to extract relevant parameters (P_T, phi, d)
- do all this with
  - sufficient speed to be used at trigger level (~20μs)
  - sufficient impact parameter precision (~40μm)



Very Large Scale Integration

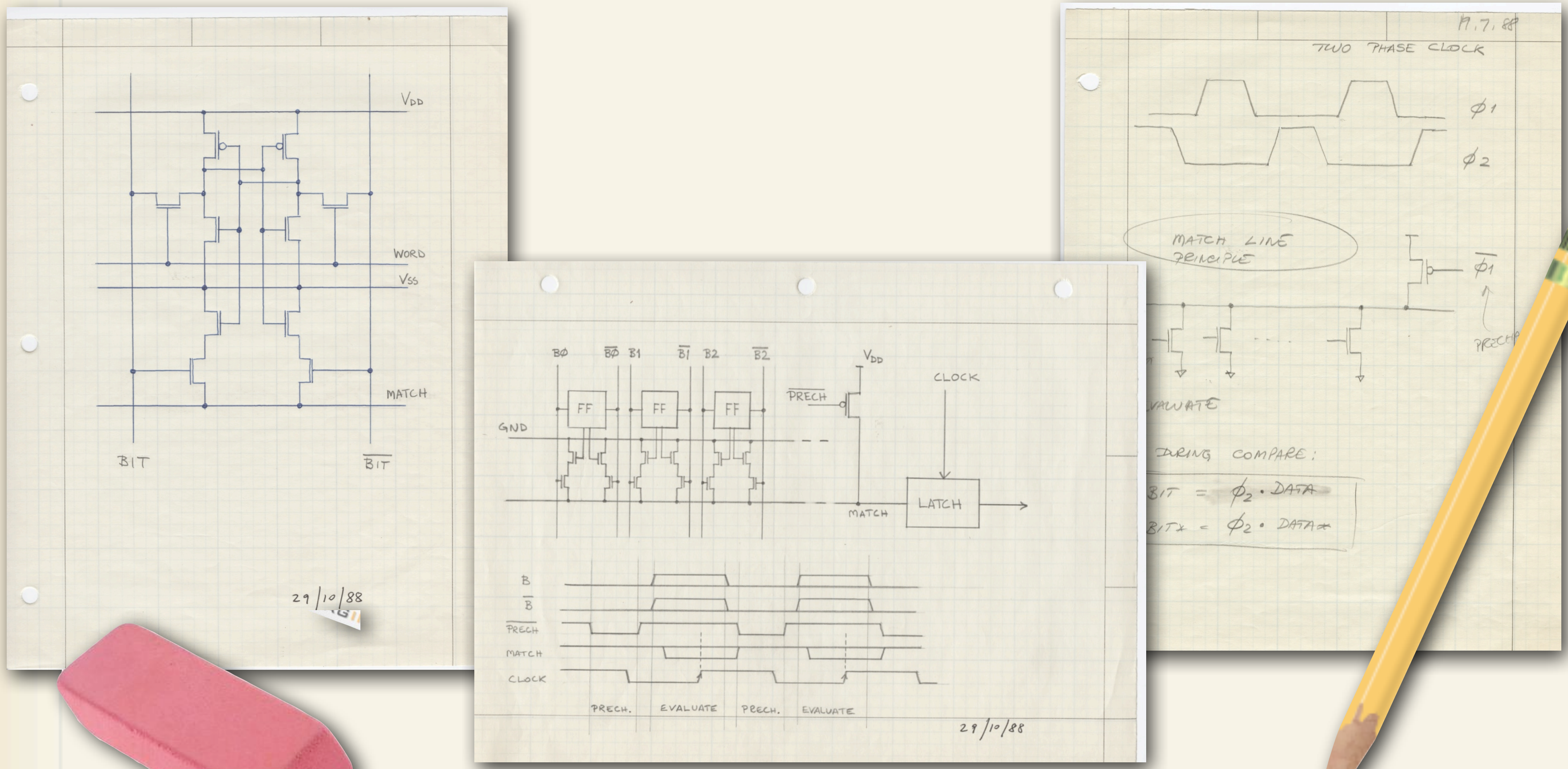
the revolution

Carver Mead & Lynn Conway

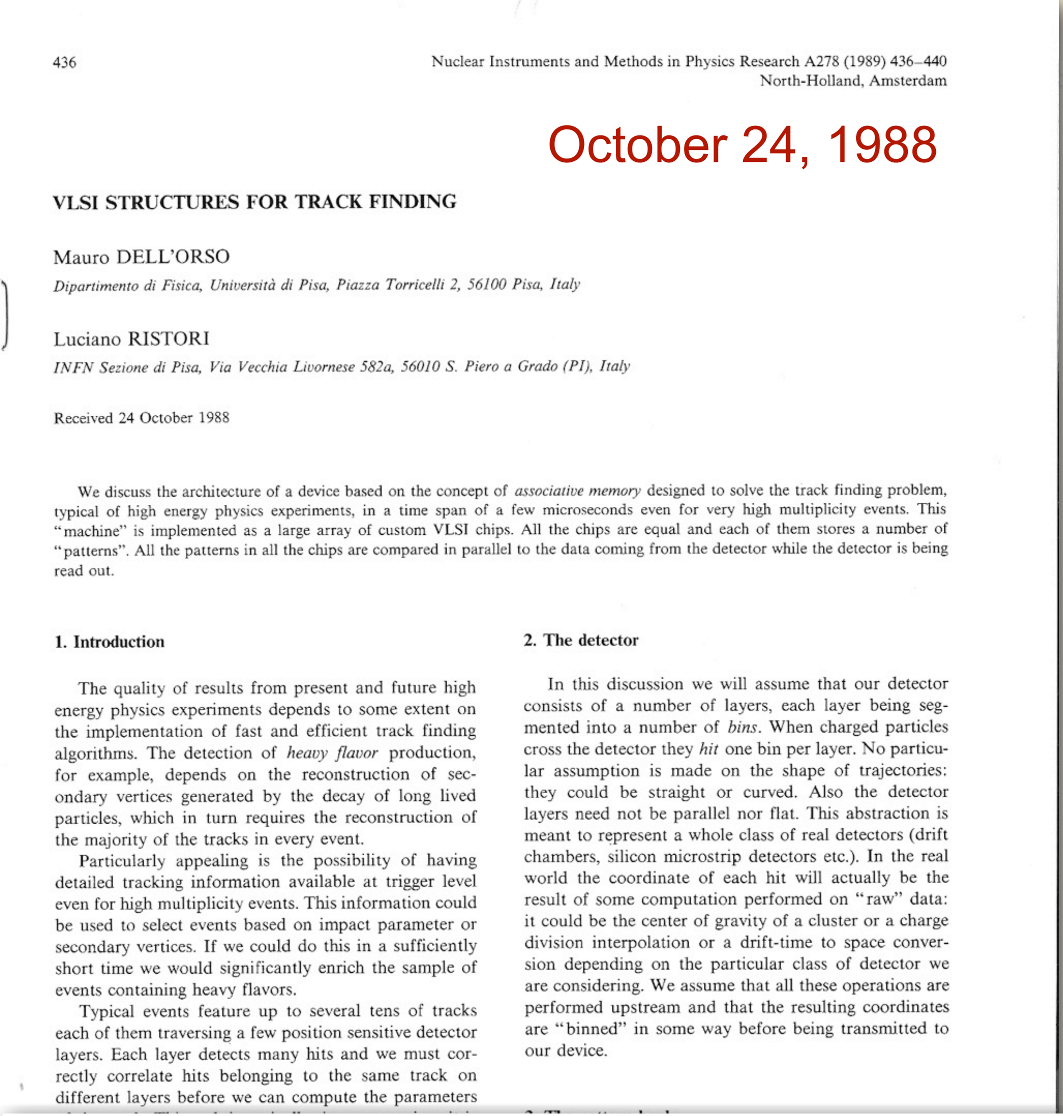

INTRODUCTION TO VLSI SYSTEMS

CARVER MEAD · LYNN CONWAY

in the '80s the technology of VLSI design becomes available to the universities and to small research projects it is at this point in time that we came up with the idea to use VLSI technology to solve the pattern recognition problem and reconstruct tracks in the detector in a very short time



October 1988: paper, pencil, eraser....



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October 24, 1988

VLSI STRUCTURES FOR TRACK FINDING

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Received 24 October 1988

We discuss the architecture of a device based on the concept of *associative memory* designed to solve the track finding problem, typical of high energy physics experiments, in a time span of a few microseconds even for very high multiplicity events. This "machine" is implemented as a large array of custom VLSI chips. All the chips are equal and each of them stores a number of "patterns". All the patterns in all the chips are compared in parallel to the data coming from the detector while the detector is being read out.

1. Introduction

The quality of results from present and future high energy physics experiments depends to some extent on the implementation of fast and efficient track finding algorithms. The detection of *heavy flavor* production, for example, depends on the reconstruction of secondary vertices generated by the decay of long lived particles, which in turn requires the reconstruction of the majority of the tracks in every event.

Particularly appealing is the possibility of having detailed tracking information available at trigger level even for high multiplicity events. This information could be used to select events based on impact parameter or secondary vertices. If we could do this in a sufficiently short time we would significantly enrich the sample of events containing heavy flavors.

Typical events feature up to several tens of tracks each of them traversing a few position sensitive detector layers. Each layer detects many hits and we must correctly correlate hits belonging to the same track on different layers before we can compute the parameters

2. The detector

In this discussion we will assume that our detector consists of a number of layers, each layer being segmented into a number of *bins*. When charged particles cross the detector they *hit* one bin per layer. No particular assumption is made on the shape of trajectories: they could be straight or curved. Also the detector layers need not be parallel nor flat. This abstraction is meant to represent a whole class of real detectors (drift chambers, silicon microstrip detectors etc.). In the real world the coordinate of each hit will actually be the result of some computation performed on "raw" data: it could be the center of gravity of a cluster or a charge division interpolation or a drift-time to space conversion depending on the particular class of detector we are considering. We assume that all these operations are performed upstream and that the resulting coordinates are "binned" in some way before being transmitted to our device.

M. Dell'Orso, L. Ristori / VLSI structures for track finding

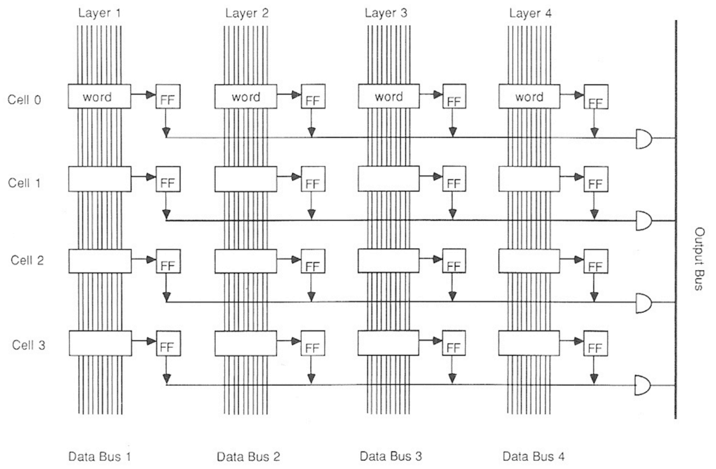


Fig. 3. Associative memory architecture.

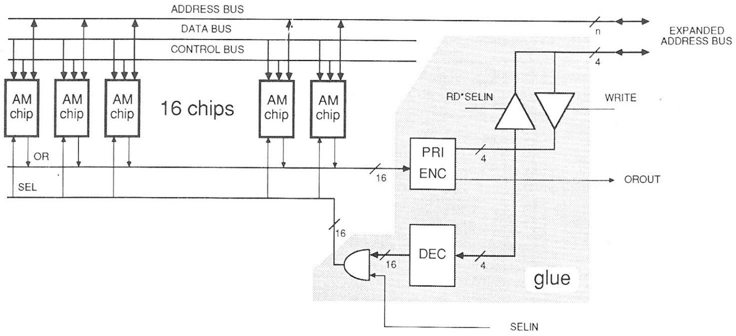
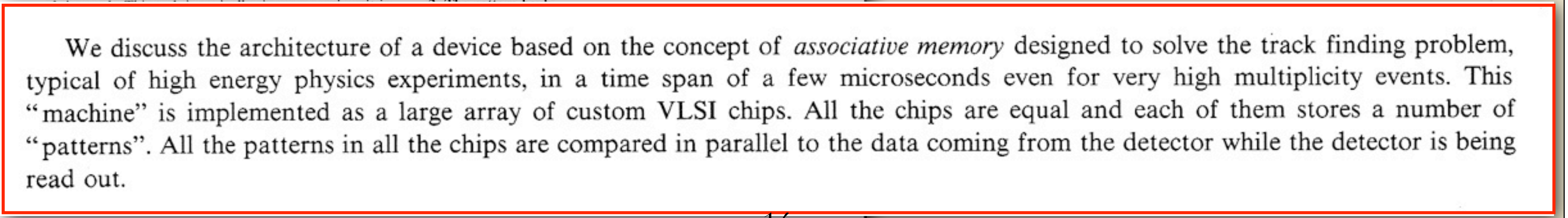
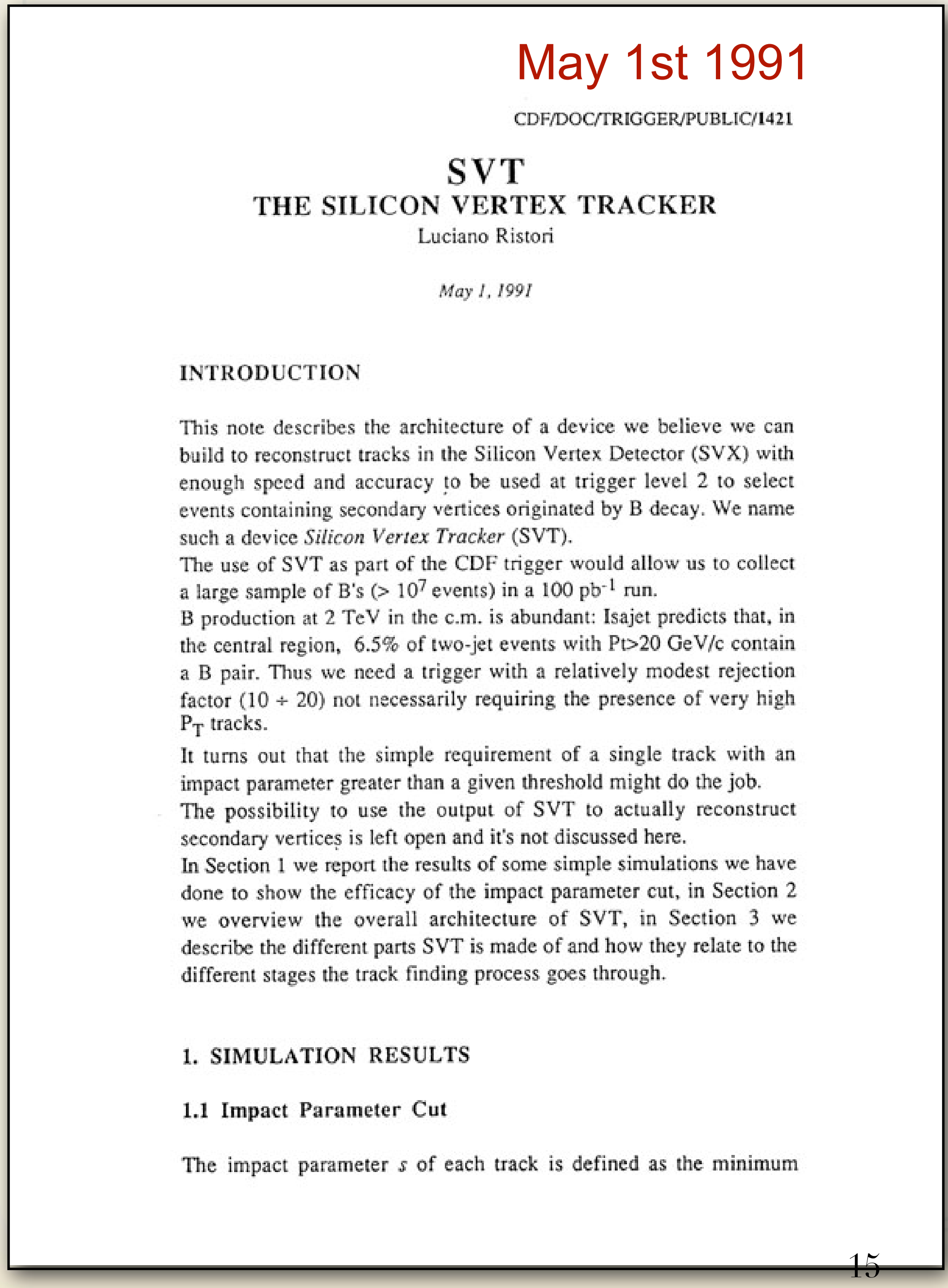


Fig. 5. 16 AM chips tied by the "glue".



We discuss the architecture of a device based on the concept of *associative memory* designed to solve the track finding problem, typical of high energy physics experiments, in a time span of a few microseconds even for very high multiplicity events. This "machine" is implemented as a large array of custom VLSI chips. All the chips are equal and each of them stores a number of "patterns". All the patterns in all the chips are compared in parallel to the data coming from the detector while the detector is being read out.



May 1st 1991

CDF/DOC/TRIGGER/PUBLIC/1421

SVT
THE SILICON VERTEX TRACKER

Luciano Ristori

May 1, 1991

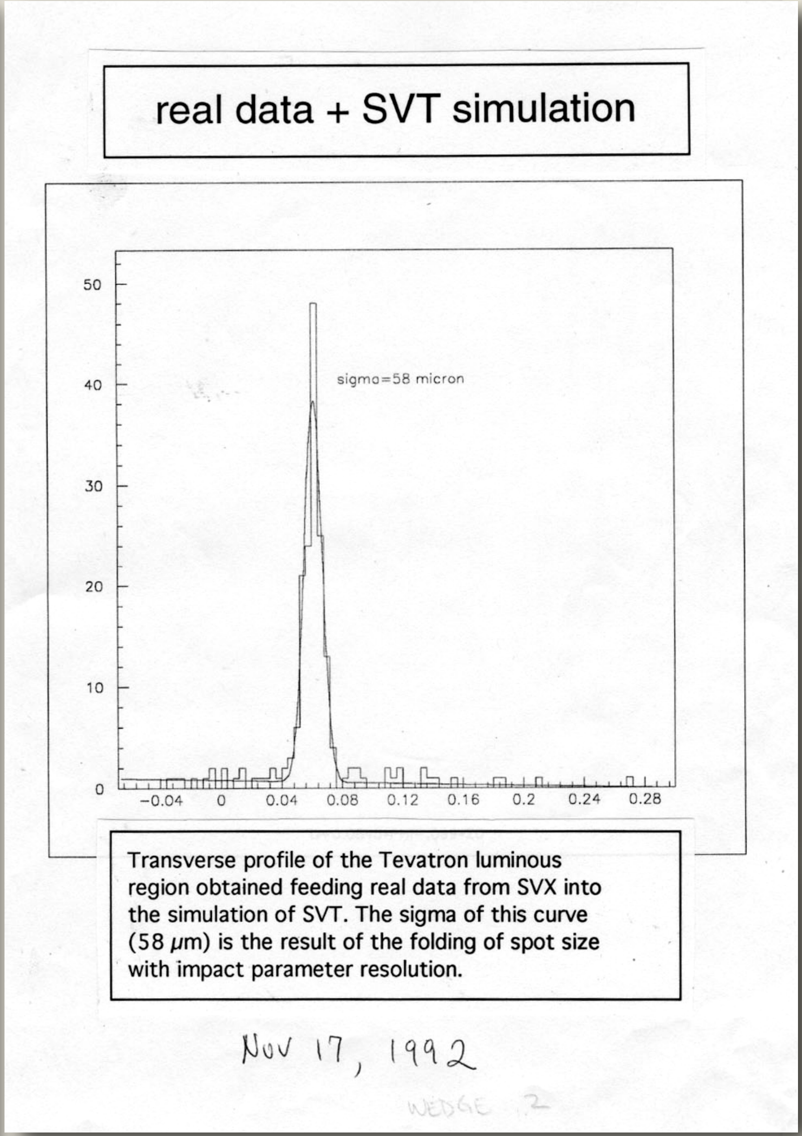
INTRODUCTION

This note describes the architecture of a device we believe we can build to reconstruct tracks in the Silicon Vertex Detector (SVX) with enough speed and accuracy to be used at trigger level 2 to select events containing secondary vertices originated by B decay. We name such a device *Silicon Vertex Tracker* (SVT).
The use of SVT as part of the CDF trigger would allow us to collect a large sample of B's (> 10^7 events) in a 100 pb^{-1} run.
B production at 2 TeV in the c.m. is abundant: Isajet predicts that, in the central region, 6.5% of two-jet events with Pt>20 GeV/c contain a B pair. Thus we need a trigger with a relatively modest rejection factor ($10 \div 20$) not necessarily requiring the presence of very high P_T tracks.
It turns out that the simple requirement of a single track with an impact parameter greater than a given threshold might do the job.
The possibility to use the output of SVT to actually reconstruct secondary vertices is left open and it's not discussed here.
In Section 1 we report the results of some simple simulations we have done to show the efficacy of the impact parameter cut, in Section 2 we overview the overall architecture of SVT, in Section 3 we describe the different parts SVT is made of and how they relate to the different stages the track finding process goes through.

1. SIMULATION RESULTS

1.1 Impact Parameter Cut

The impact parameter s of each track is defined as the minimum



real data + SVT simulation

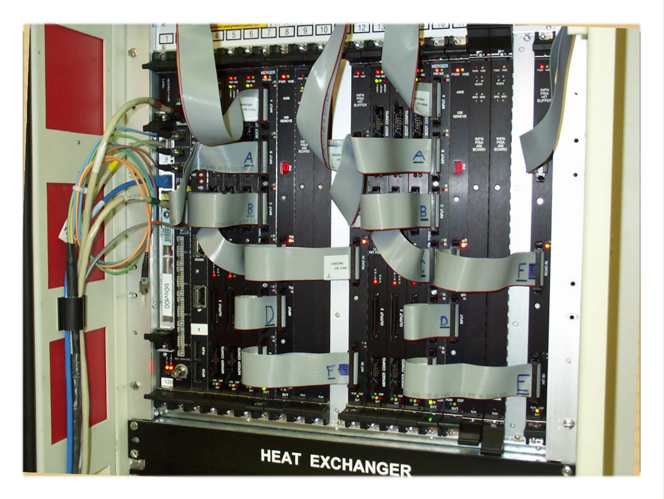
Transverse profile of the Tevatron luminous region obtained feeding real data from SVX into the simulation of SVT. The sigma of this curve (58 μm) is the result of the folding of spot size with impact parameter resolution.

Nov 17, 1992

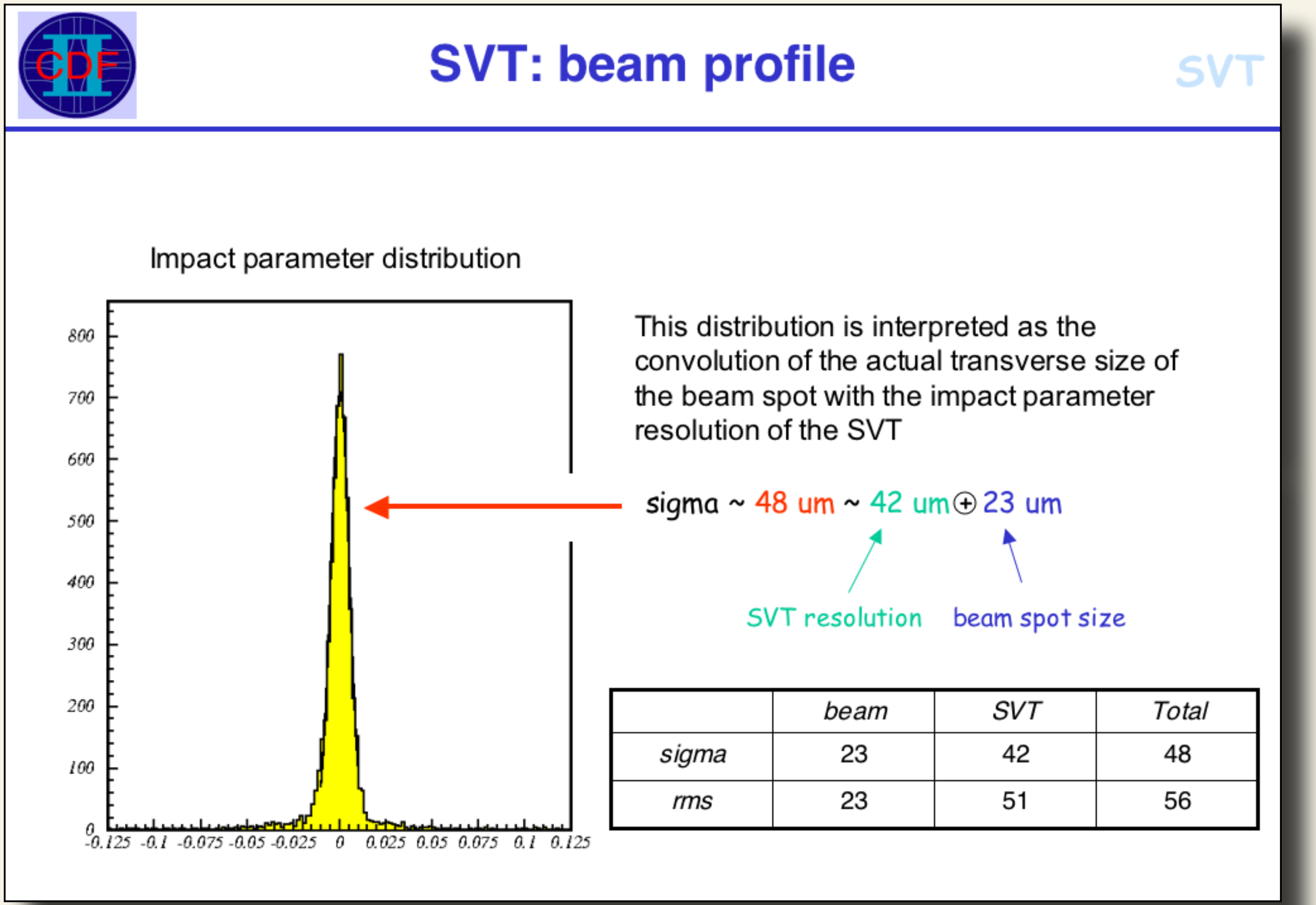
WEDGE 2

All SVT boards installed in the CDF trigger room

August 2000



the precision of the measurement of the impact parameter is as expected



SVT: beam profile

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

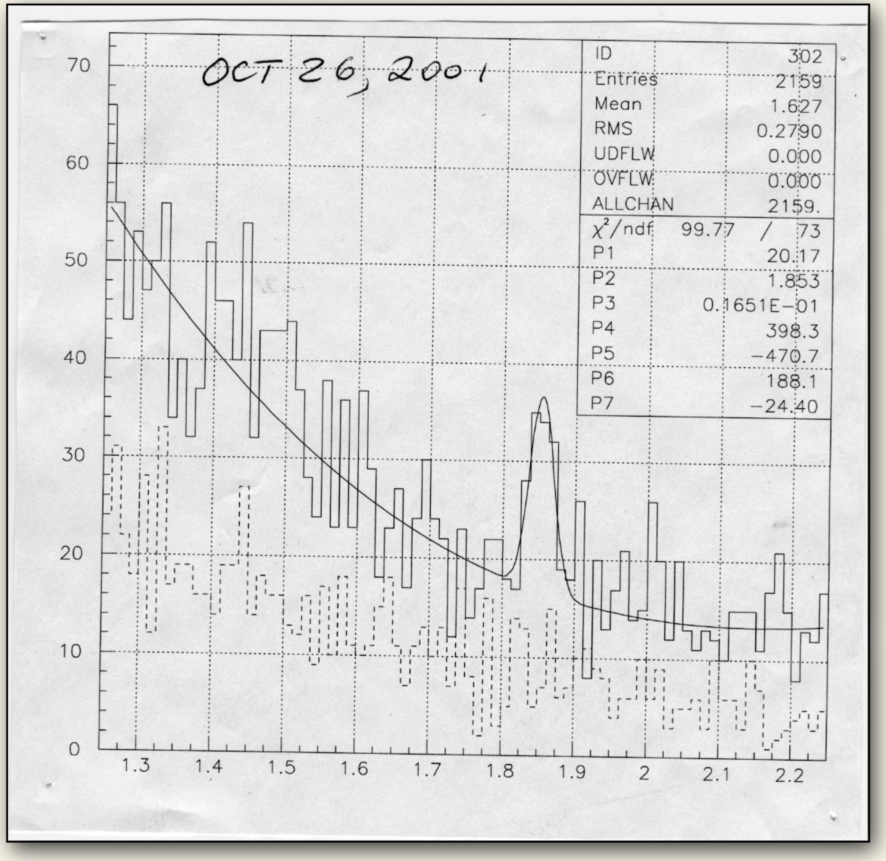
sigma ~ 48 um ~ 42 um ⊕ 23 um

SVT resolution

beam spot size

	beam	*SVT*	*Total*
sigma	23	42	48
rms	23	51	56

October 2001: the next important milestone



OCT 26, 2001

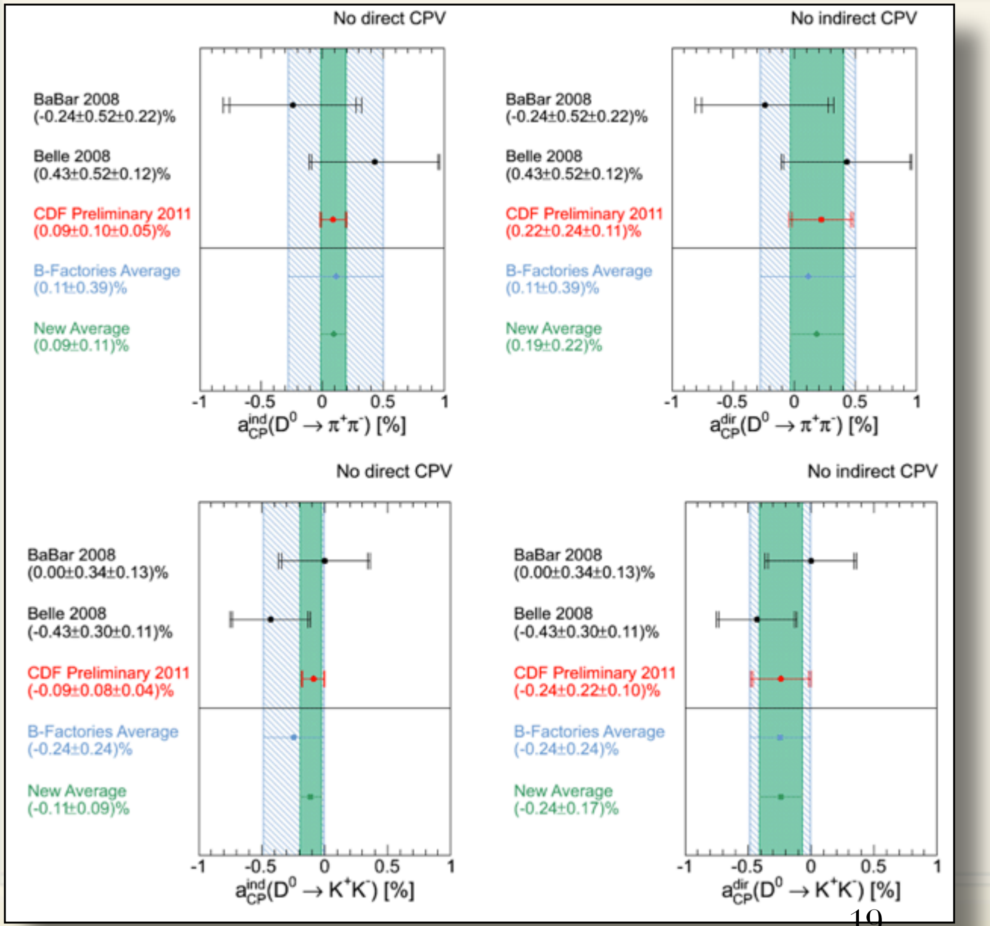
```
ID                  302
Entries            2159
Mean              1.627
RMS              0.2790
UDFLW             0.000
OVFLW             0.000
ALLCHAN           2159.
χ²/ndf   99.77  /    73
P1                20.17
P2                1.853
P3           0.1651E-01
P4                398.3
P5               -470.7
P6                188.1
P7               -24.40
```

D^0 signal in the events selected by SVT

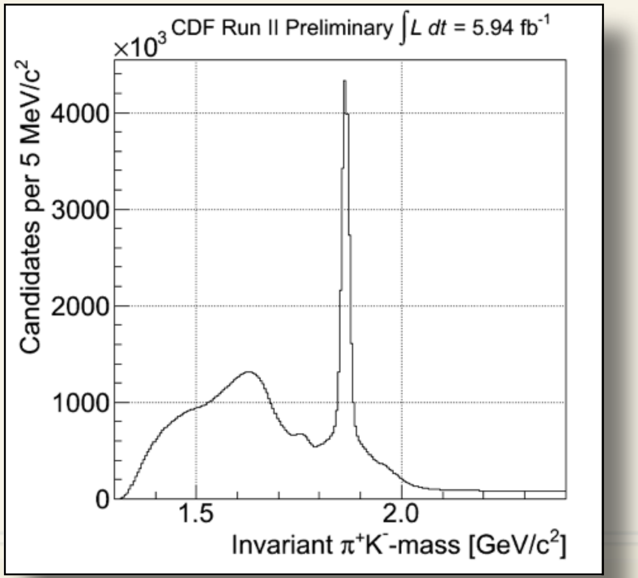
Search for CP Violation in $D^0 \rightarrow \pi^+\pi^-$ and K^+K^-

compare to B factories

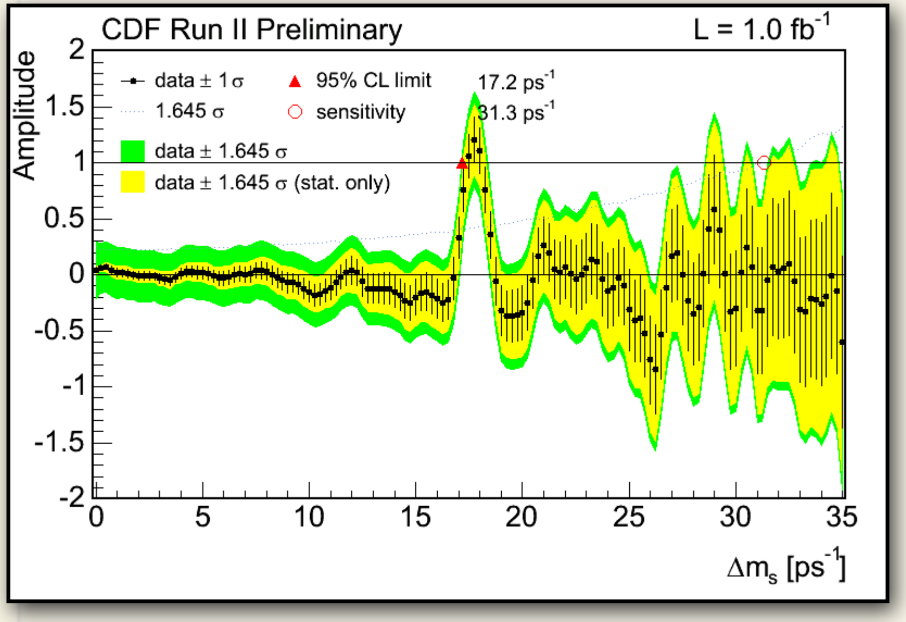
$$A_{CP}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$



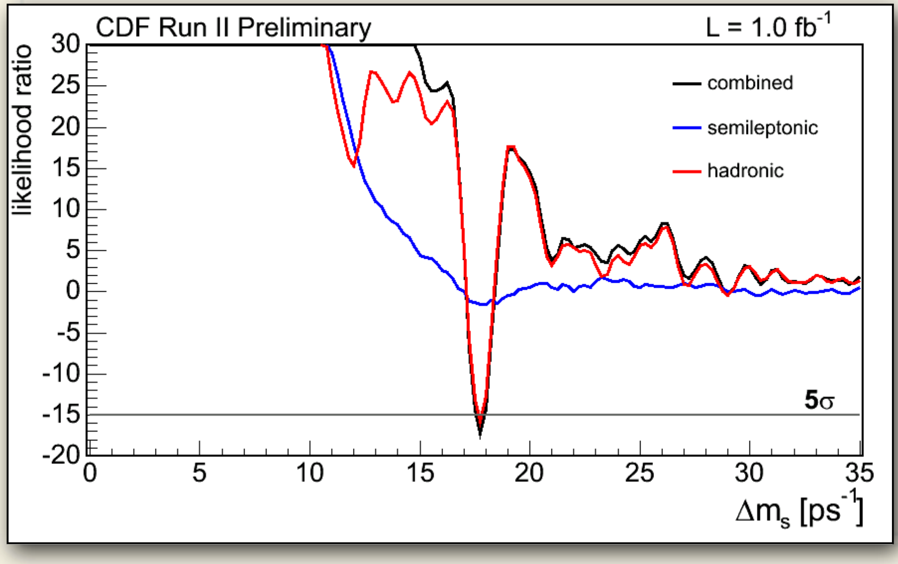
thanks to SVT, CDF has the
world’s largest sample
of two-body decays of D^0 mesons
(~ 30 million decays)

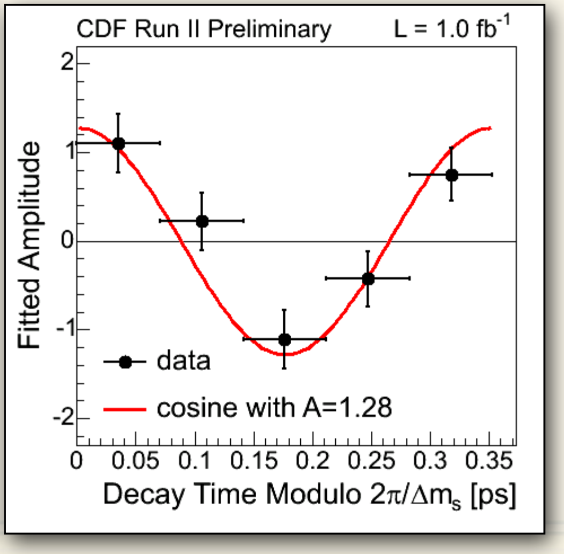


Observation of B_s^0-$\bar{B}_s^0$ Oscillations

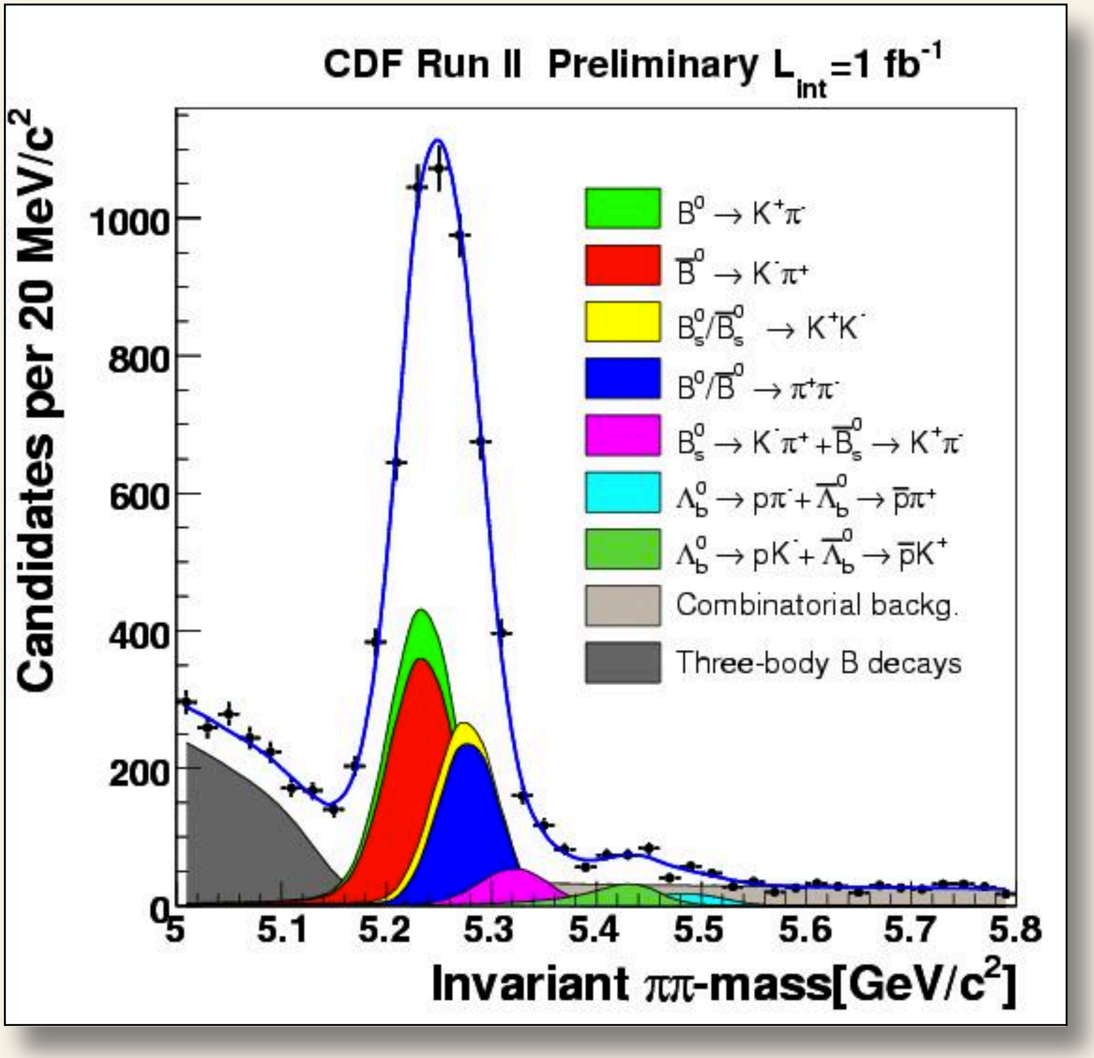


the quality of this measurement is essentially determined by the hadronic decays selected by the SVT trigger





$B \rightarrow h^+h^-$ and $\Lambda_b \rightarrow h^+h^-$



a success story

- SVX was crucial for the discovery of the Top quark
- SVXII is now crucial for the search for the Higgs
- The addition of SVT has allowed CDF to be competitive with the B factories in terms of yield of Charm and Beauty
- Also it opened up the sector of hadronic decays of heavy flavored mesons and barions not accessible to the B factories (B_s, B_c, Λ_b,...)

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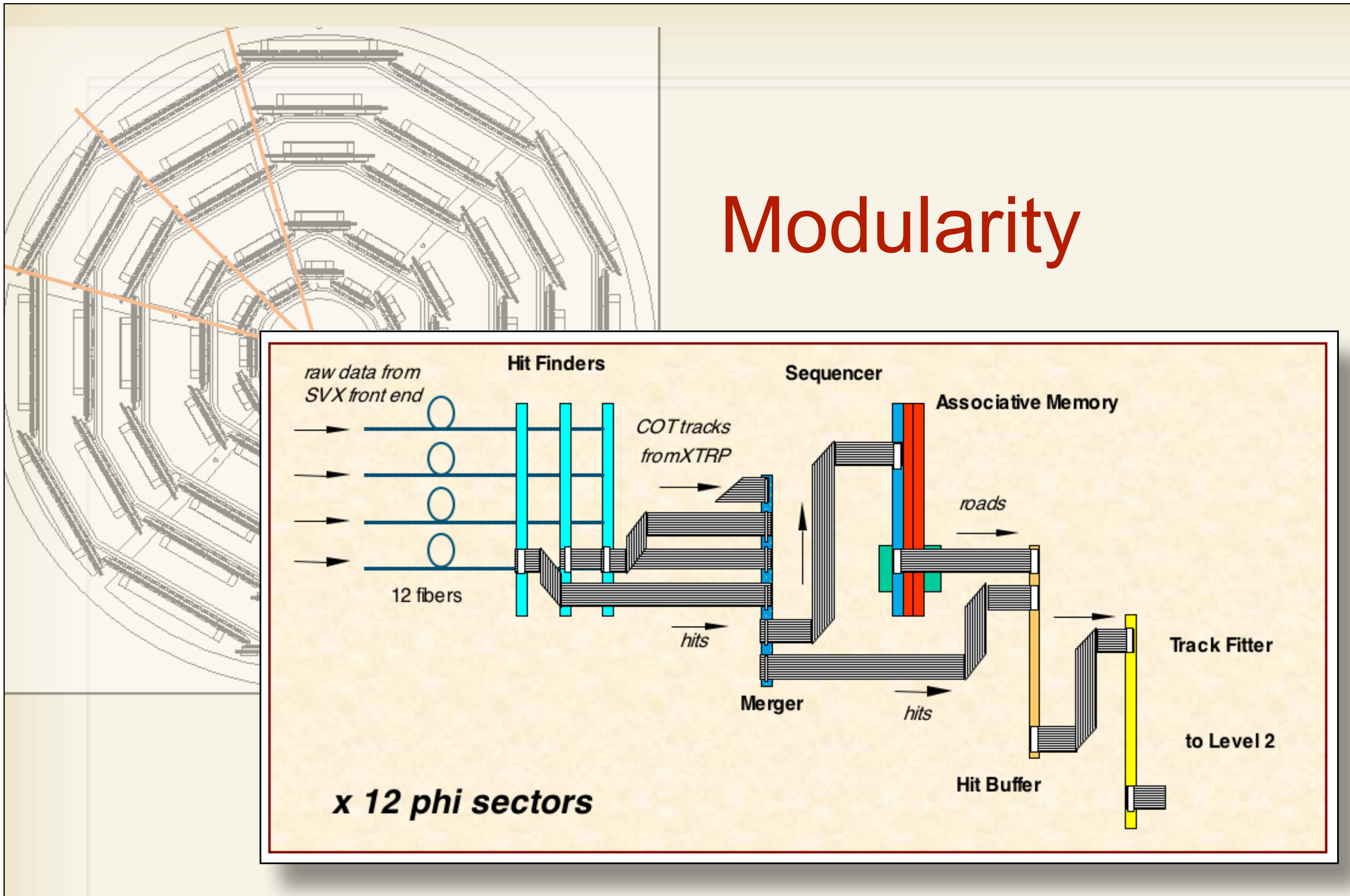
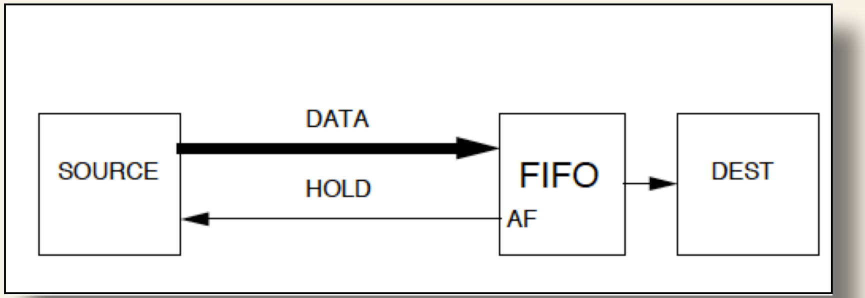
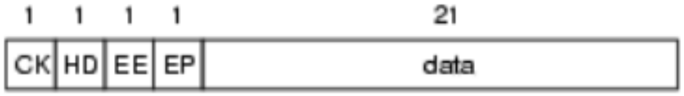
Modularity



- more than 100 VME boards of a dozen different types
- data flow through point-to-point cables
- controlled through VME interface
- board to board communication protocol is uniform throughout the system

uniform communication protocol





CK = Clock
HD = Hold
EE = End Event
EP = End Packet

- Asynchronous clocks
- FIFO Buffers
- HOLD when “Almost Full”
- Uniform:
  - data format
  - electrical specs
  - mechanical specs

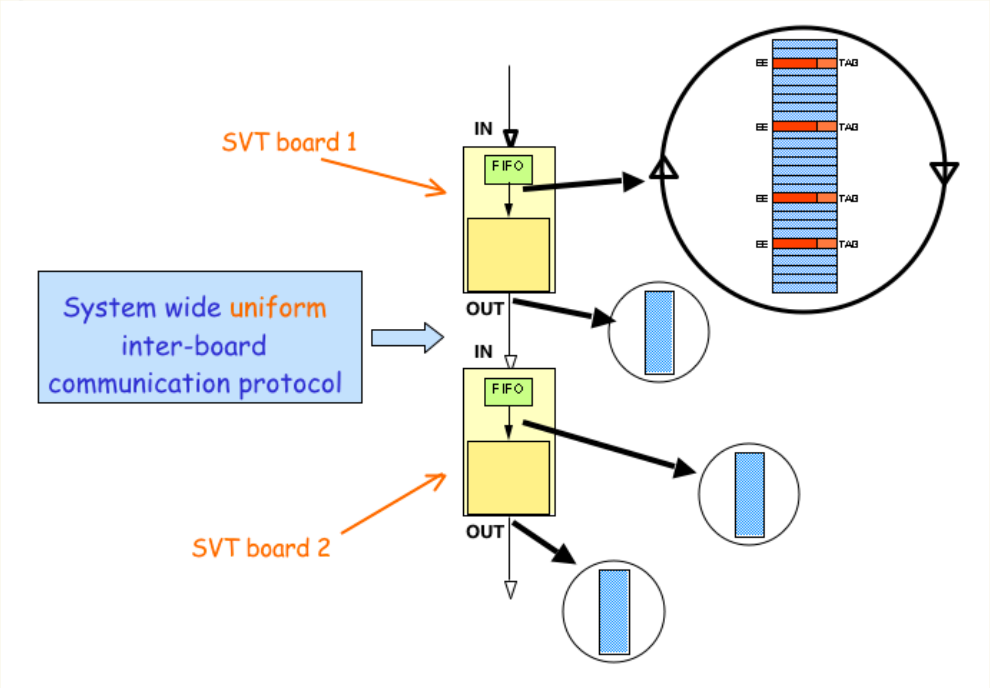
⇓

- Full modularity
- Improved testability

diagnostics

- powerful handles designed in the hardware
    - parity checking
    - error flags propagated in the data stream
    - write inputs & read outputs

spy buffers



Circular buffers are placed on all inputs and outputs of each board. They work as built-in logic state analyzers.

They can be triggered by a number of events including detection of error conditions and are read out through the VME interface

They can be used also as data sources to test the system at speed

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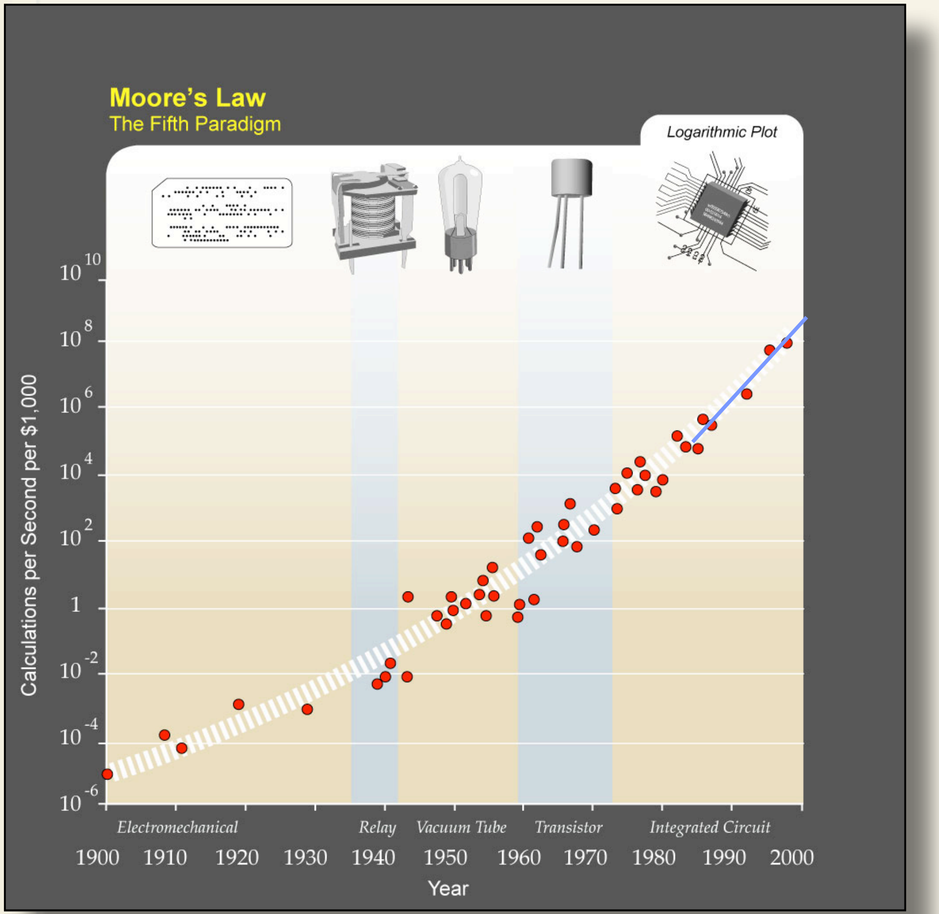
need to beat Moore’s law

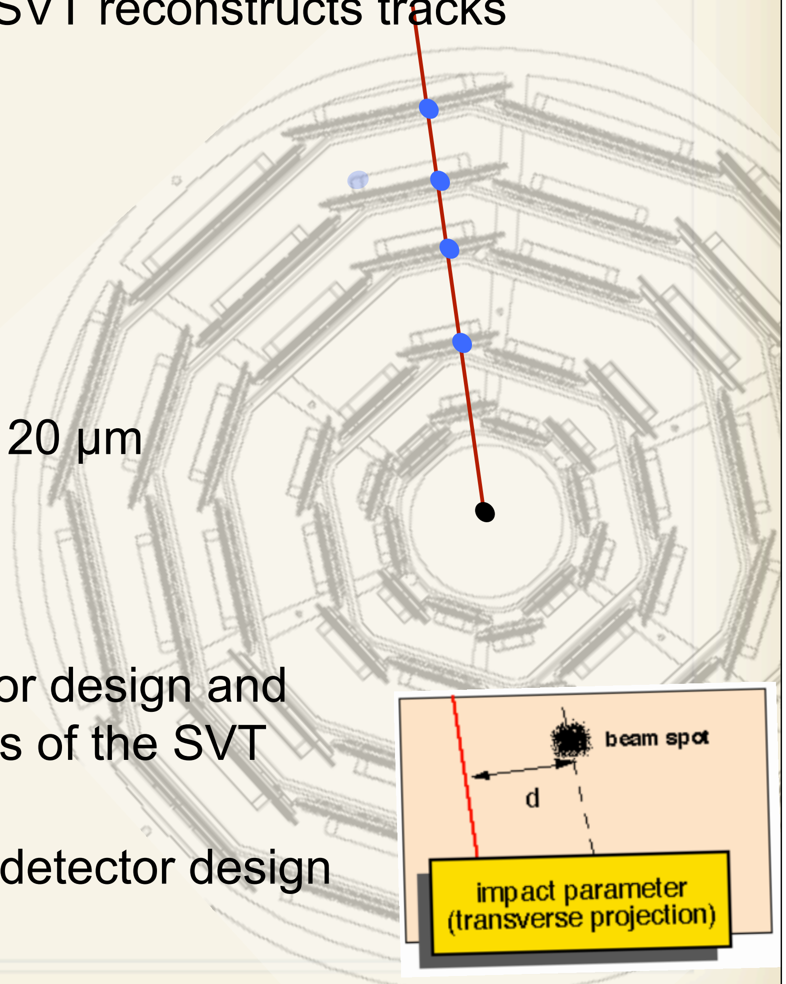
calculations/second/$1000



- factor x100 in 10 years
- if you design custom electronics for doing computation that is going to be installed 10 years later, you need to beat what’s available off the shelf at least by a factor 100
- the design of the SVT was very aggressive (crazy?). Relied on the most advanced technology available to us at the time (A.D. 1990)
- it was risky but it was crucial to survive 10 years of Moore’s law growth

detector specs driven by trigger requirements

- 3D track reconstruction was way too hard: SVT reconstructs tracks in the transverse plane (2D)
- Requirements:
  - Si strips parallel to the beam
  - mechanical alignment of detector at ~ 20 μm
  - alignment of beam ~ 100 μrad
- resulted in a very significant effort in detector design and construction that was crucial for the success of the SVT
- Lesson learned: trigger requirements drive detector design



physics motivations

- when we embark in a new project it is very important to have solid physics motivations, but...
- most of the times we cannot really predict what we will actually end up doing many years along the road since physics motivations are very much time dependent
- one of the main physics motivations that we used throughout the whole design and approval phase of SVT was the time dependent analysis of the “golden channel” B^0 to $\pi^+ \pi^-$
- in the end we did many things, but not B^0 to $\pi^+ \pi^-$, partly because it lost some theoretical interest, partly because it is probably too difficult. Other processes turned out to be much more interesting (B^0 to $K\pi$, B_s oscillations, B_s to J/Psi phi,...)
- maybe one should conclude that it is much safer to say that if you significantly improve the performance of your detector the physics will necessarily follow...

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individual commitment to “make it work”

- in this era of very large collaborations and shared responsibilities, all in the end still relies on the commitment of single individuals who take on them the burden, the sweat and the tears to “make it work” not because of the credit they think they might get out of that, but just because they want to do it
- we owe a big thank to all of them!

taking risks

- SVT was a very risky project and might have failed for many reasons including some that were totally out of our control. In this respect, we were very lucky
- we need to go back to taking risks, this is what “research” is all about
- you cannot innovate if there is no room for failure
- the progress of science is based on trial and error
- the reward system must be based on the quality of the effort and not necessarily on the final outcome
- sometimes a “failure” may be as important to the progress of science as a success

innovative thinking

to the young people:

- it is still possible to come up with innovative ideas, work hard to make them work, and have a significant impact on the progress of our field

to the seniors:

- we need to reward innovative thinking, taking risks and allowing some room for failure as opposed to going with the current flow where every single project needs to be “guaranteed to succeed”