Life on the Critical Path

Constructing Silicon Detectors for Hadron colliders:
(CDF and CMS)

Joe Incandela
University of California, Santa Barbara
6^{th} International Hiroshima Symposium
Carmel, California
September 13, 2006

Prologue

- A string of overlapping Si detector, & related, projects since 1991.
  - CDF: SVX' ISL Layer 00 Run 2b
  - Silicon Detector Center at FNAL
  - CMS: Silicon strip tracker
- All of these were, or are, *critical path* projects
  - *This is mostly a nice way of saying behind schedule.*
- Recently completed US production effort for CMS

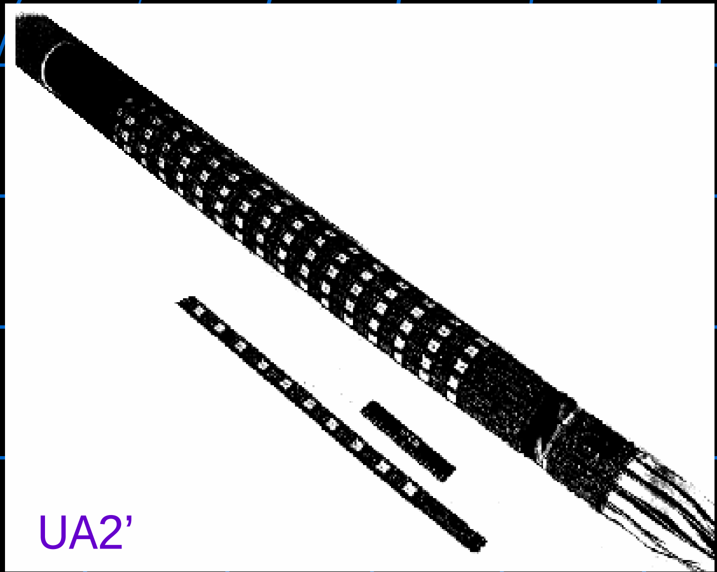
So I thought it could be fun to reflect on this 15 y period …

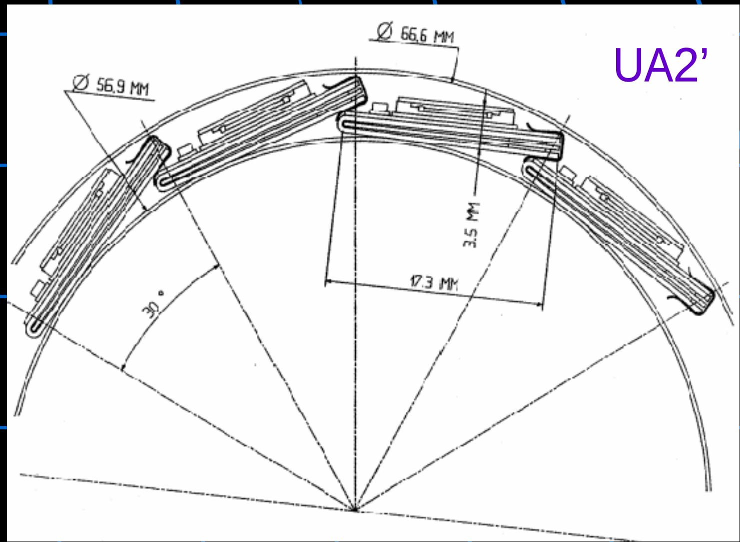
Outline

- Some history *(neither complete nor unbiased)* of Silicon at Hadron Colliders
  - Silicon B.C.
    - **B**efore **C**omputers were used to write notes and talks…
  - CDF's 1st Vertex detector: SVX (1992-1993)
  - CDF's 1st "Rad-hard" Vertex detector: SVX' (1993-1996)
  - CDF Silicon for Run II:
    - SVXII
    - ISL
    - Layer 00
- Finally an <u>All Silicon Tracker: CMS</u>

collider silicon detectors

Si Microstrip Detectors: A New tool for HEP (E. Heijne, P. Jarron) c. 1981





- Silicon pad detectors in UA2: 1st operation 1987
  - Mounted directly to the beampipe
- And, of course, the e^+e^- collider experiments …

Start of CDF Silicon

A. Menzione & C. Haber

Collaboration: PISA/FNAL/LBNL…

- D. Amidei first project leader
- P. Tipton took over around 1990

CDF Note No. 455
May 1986

The Silicon Vertex (SVX) of CDF

R. Kephart, A. Tollestrup
Fermi National Accelerator Laboratory

W. Carithers, R. Ely, C. Haber
S. Kleinfelder, H. Spieler
Lawrence Berkeley Laboratory

F. Bedeschi, G. Bellettini, G. Chiarelli, E. Focardi
A. Menzione, L. Ristori, G. Tonelli
INFN, Pisa, Italy

CDF- 475
May 8, 1986

An Evaluation of the MICROPLEX Amplifier for Use in the CDF Silicon Vertex Detector

Carl Haber
Lawrence Berkeley Laboratory

CDF-593
Dec., 1987

TEST RESULTS OF TWO LBL SVX SILICON STRIP DETECTOR READOUT CHIPS AND THE LBL RADTEST CHIP

Tom Zimmerman, R. Yarema
Fermilab

I. INTRODUCTION

Two versions of a silicon strip detector readout chip built by S. Kleinfelder and others at LBL have been received at Fermilab. Version

P-775

PROPOSAL P-775

To upgrade CDF with a Silicon Vertex Detector in order to tag long-lived heavy flavors

1. Introduction and Summary

This document is a proposal to upgrade CDF with a silicon strip micro-vertex detector (the CDF SVX). The addition of this device to CDF would permit the tagging of the decays of long-lived heavy particles produced in $\bar{p}p$ collisions on an event-by-event basis. This will give CDF a v
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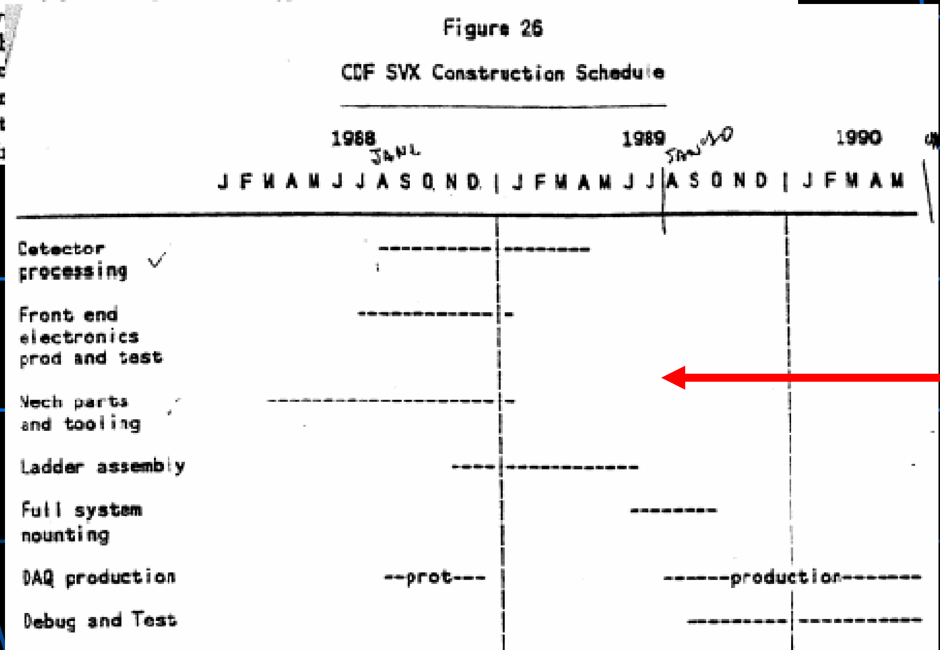
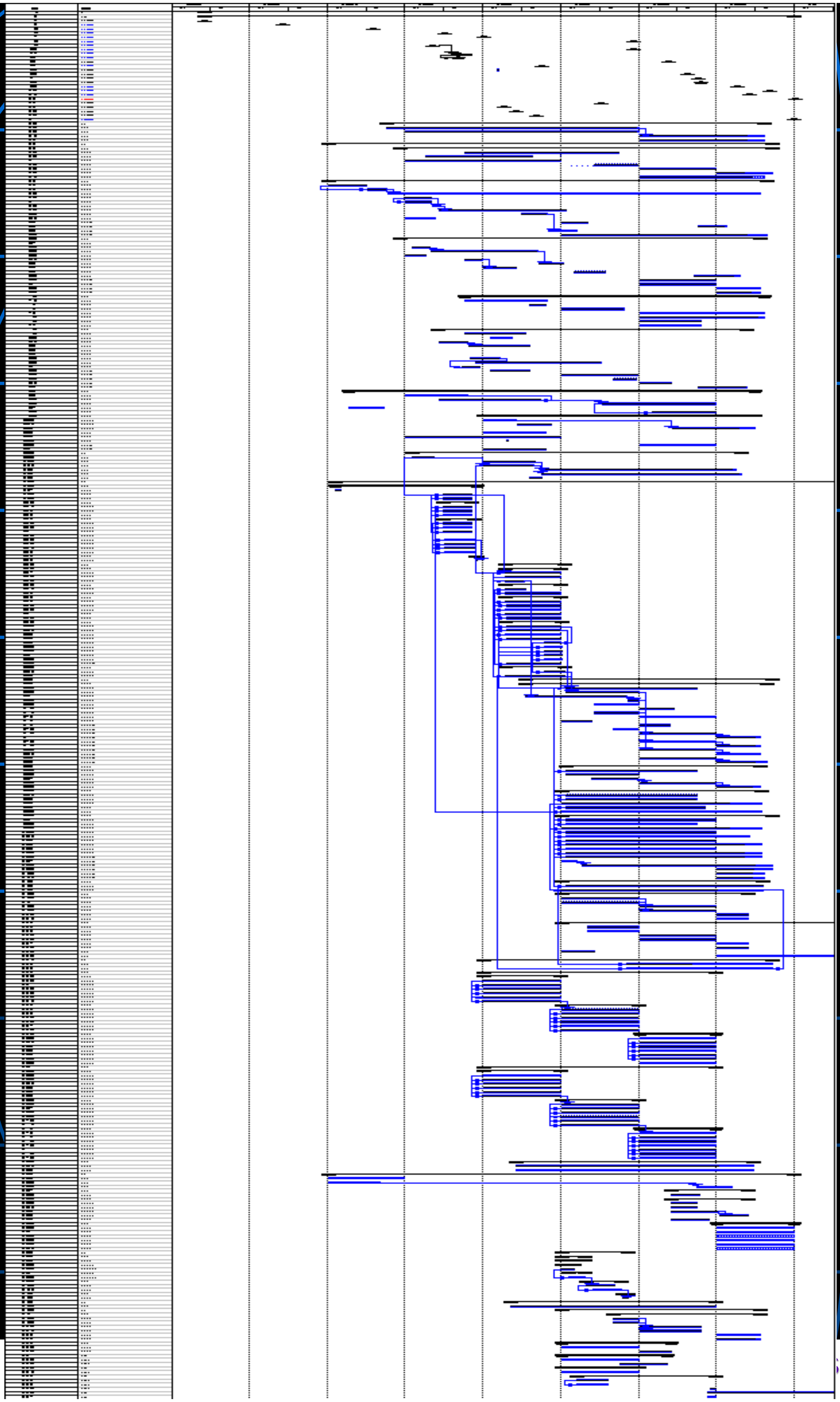


Look at this schedule!



US CMS Silicon Tracker

CDF SVX Project

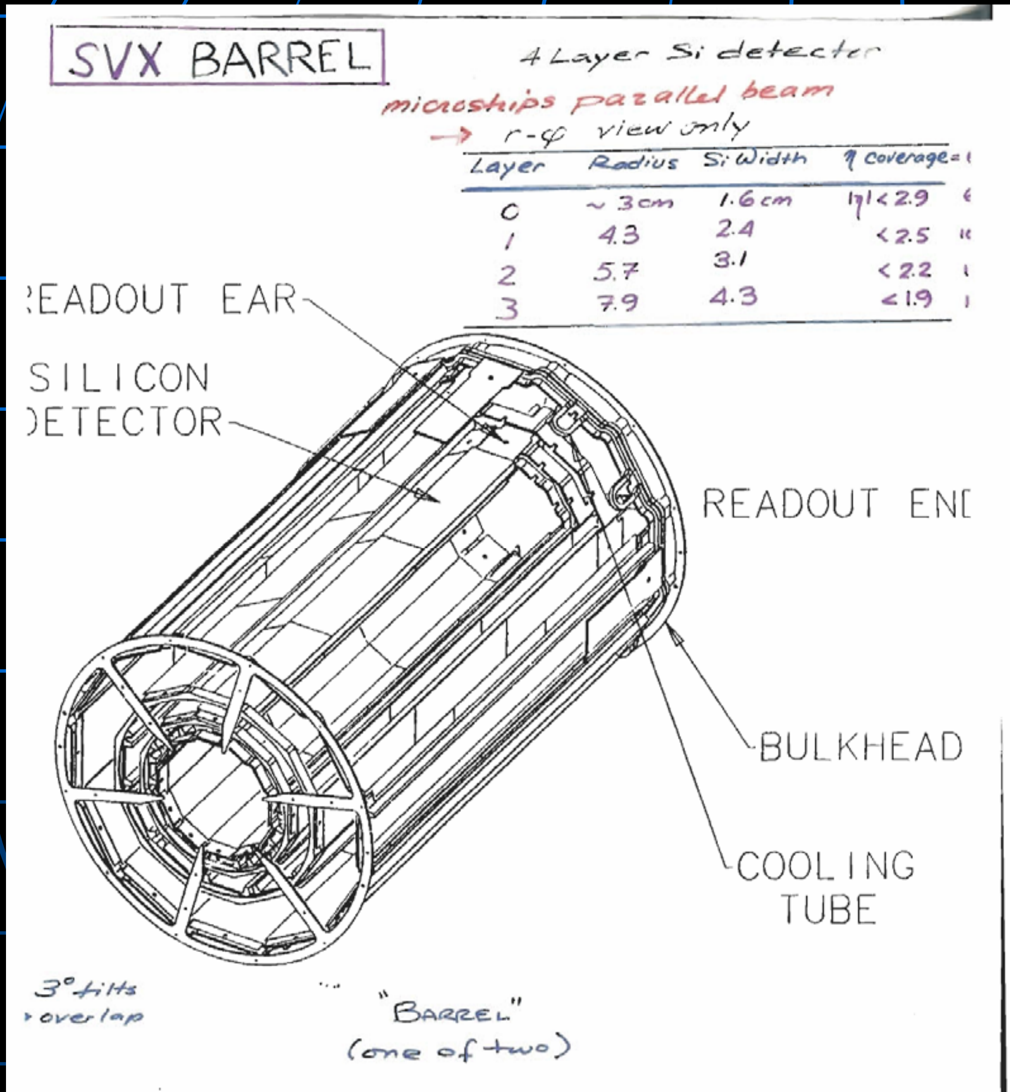
- Sensors
  - *4" wafers, DC coupled (Micron Semiconductor).*
- LBL began the SVX chip line w/FNAL
- 1st SVX chips (HP 3.5μm technology)
  - 128 channels, double correlated sample, sparse logic.
  - Soon after: a rad-hard UTMC version
    - But not in time for SVX (used in SVX').
- LBL constructed all hybrids and modules
  - Everyone flying to FNAL had to hand-carry some...
- Final assembly FNAL, 1991-1992

” I think the SVX was never really a formally approved project for CDF, but rather a prototype to prove the concept. Vertexing with silicon sensors was not considered viable at a hadron collider. I recall vividly [people] being very skeptical about all the effort … claiming at such a radius the detector would be completely lit [100% occupied] all the time.

It turned out not to be the case. “

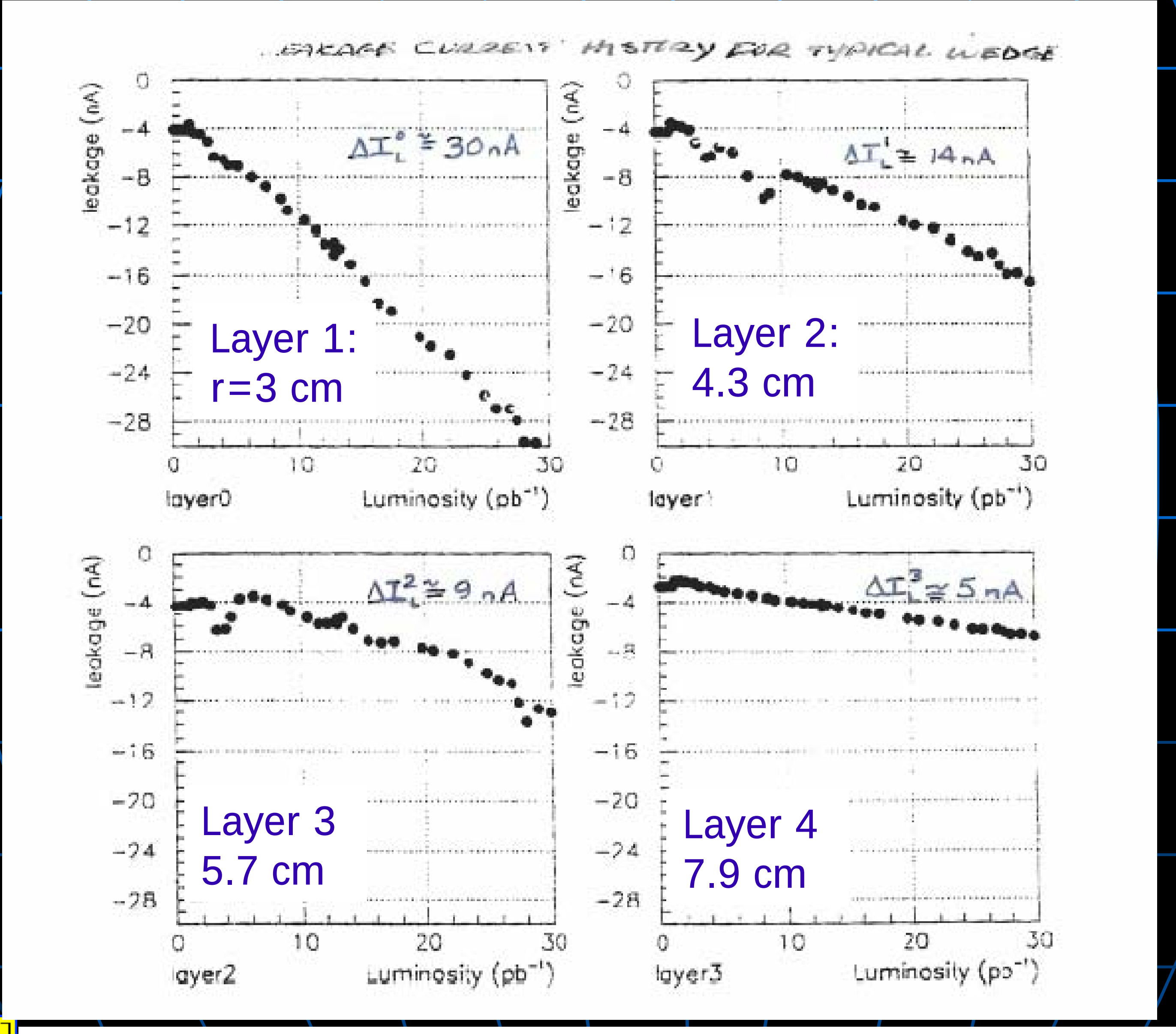
Nicola Bacchetta (INFN Padova)

SVX



- 2 barrels w/4 layers
- DC coupled
  - Quad sampled
- Rad-soft Electronics
- Major results!
  - *B decays visible*
  - *By early 1993, Amidei's b tag group had a slight excess in the tagged W+3 or more jets sample.*

SVX at end of Run 1a



~ $R^{-1.7}$ Dependence

The Demise of a Silicon Detector and Birth of a Hardier Brother

SVX

SVX D R/O CHIP – RAD SOFT CMOS

- → Detector Occupancy Rises while efficiency falls
- Fraction of tracks with N hits:

ϵ_{4HIT}	ϵ_{3HIT}	ϵ_{2HIT}
.71 → .58	.23 → .31	.05 → .09

Hit eff. by layer:

ϵ_0	ϵ_1	ϵ_2	ϵ_3
.93 → .89	.93 → .85	.93 → .91	.91 → .89

The Ingredients of SVX'

Proc. 2nd London Conf. on Position-Sens. detectors Sept. 4-7, 1990

Nuclear Instruments and Methods in Physics Research A310 (1991) 155–159
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

FOXFET biassed microstrip detectors

P.P. Allport, J.R. Carter, V. Gibson, M.J. Goodrick, J.C. Hill and S.G. Katvars
Cavendish Laboratory, University of Cambridge, Cambridge, UK

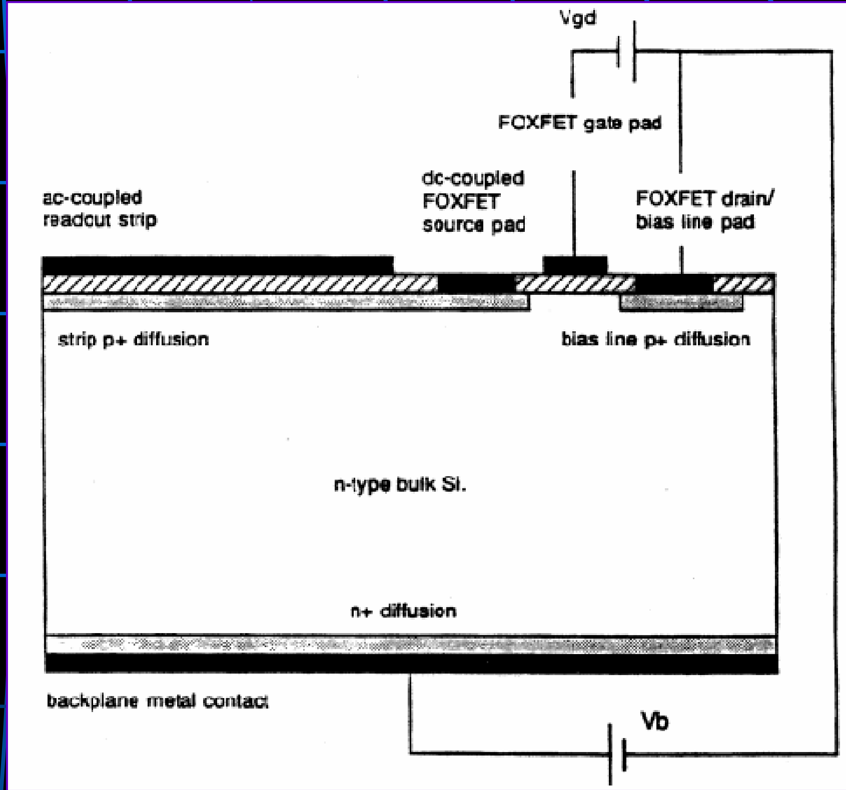
M.A. Bullough, N.M. Greenwood, A.D. Lucas and C.D. Wilburn
Micron Semiconductors Limited, Lancing, Sussex, UK

A.A. Carter and T.W. Pritchard
QMW, London University, London, UK

L. Nardini, P. Seller and S.L. Thomas
Rutherford Appleton Laboratory, Didcot, Chilton, Oxfordshire, UK

A method has been developed for biassing the strips of a silicon microstrip detector with a tunable dynamic resistance. This allows the strip potentials to be tied to a fixed voltage, virtually independent of the strip leakage currents, whilst requiring no processing steps additional to those needed for a standard capacitively coupled detector. Results are presented for full sized detectors (3.3 cm × 6.3 cm) both measured on a probe station and equipped with VLSI readout (MX3) chips. Assemblies are currently undergoing beam tests at CERN with indications of very promising performance.

AC coupled strips with FOXFET gate biasing



SVX' on the critical path

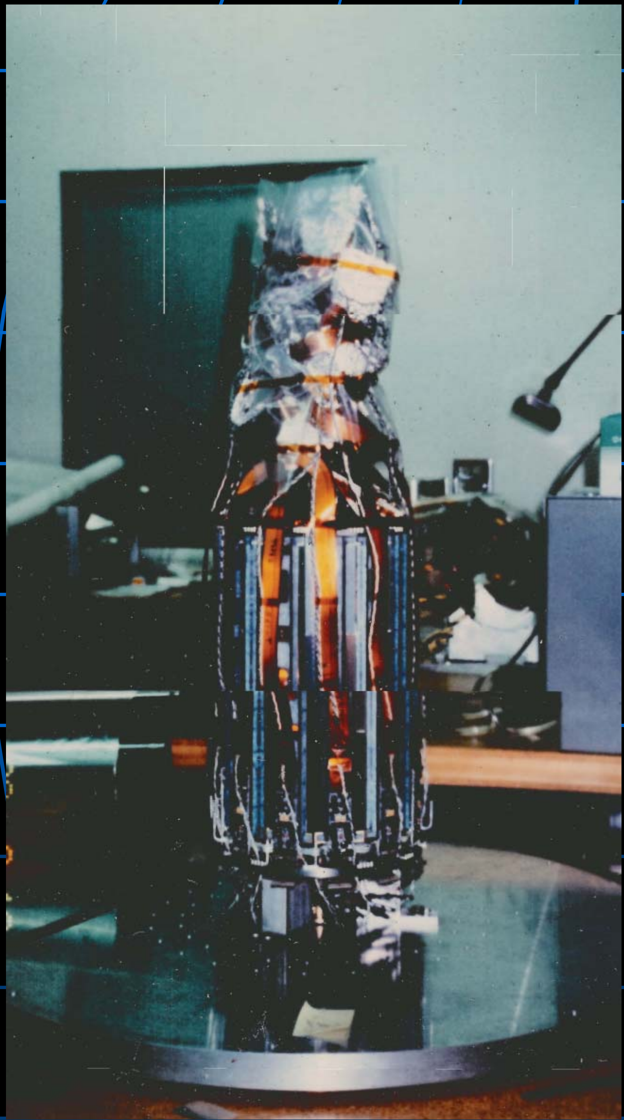
- Problems
  - Hybrids: cracks in dielectric layers
  - SVX H Chip: did not quite work as planned
- Delays
  - Schedule: install Oct. 9, 1993
  - Actual: No modules built as of mid-June!
- Miraculous recovery:
  - Changed dielectric
  - Learned to operate in double-sample mode *(R. Ely, E. Kajfasz, et al.)*
- Could finally start production: with less than 4 months to do everything!

How to build a silicon detector in a summer…

- Establish the most simple, safe, efficient procedures for every step
- Prepare for all possible problems:
  - equipment failures, loss of key personnel,…etc
- *Work 16-24 hours/day for 89 of 90 days.*

Building SVX'

Don't forget your umbrella



- SVX' on vertical stand
  - Dressed cables in preparation for installation of thermal screen
  - Aug. 20th: Screen was installed, (5 days ahead of schedule) and barrel was moved to another location
  - Aug. 21st: Ceiling overhead collapsed under weight of accumulated water

Years later…

In preparation to build the CDF and D0 Run 2 Silicon detectors, had water guards installed over the main assembly areas

In fact, ceiling collapsed under weight of water (before silicon was being built) due to failure of a water softener mounted on roof.

QA

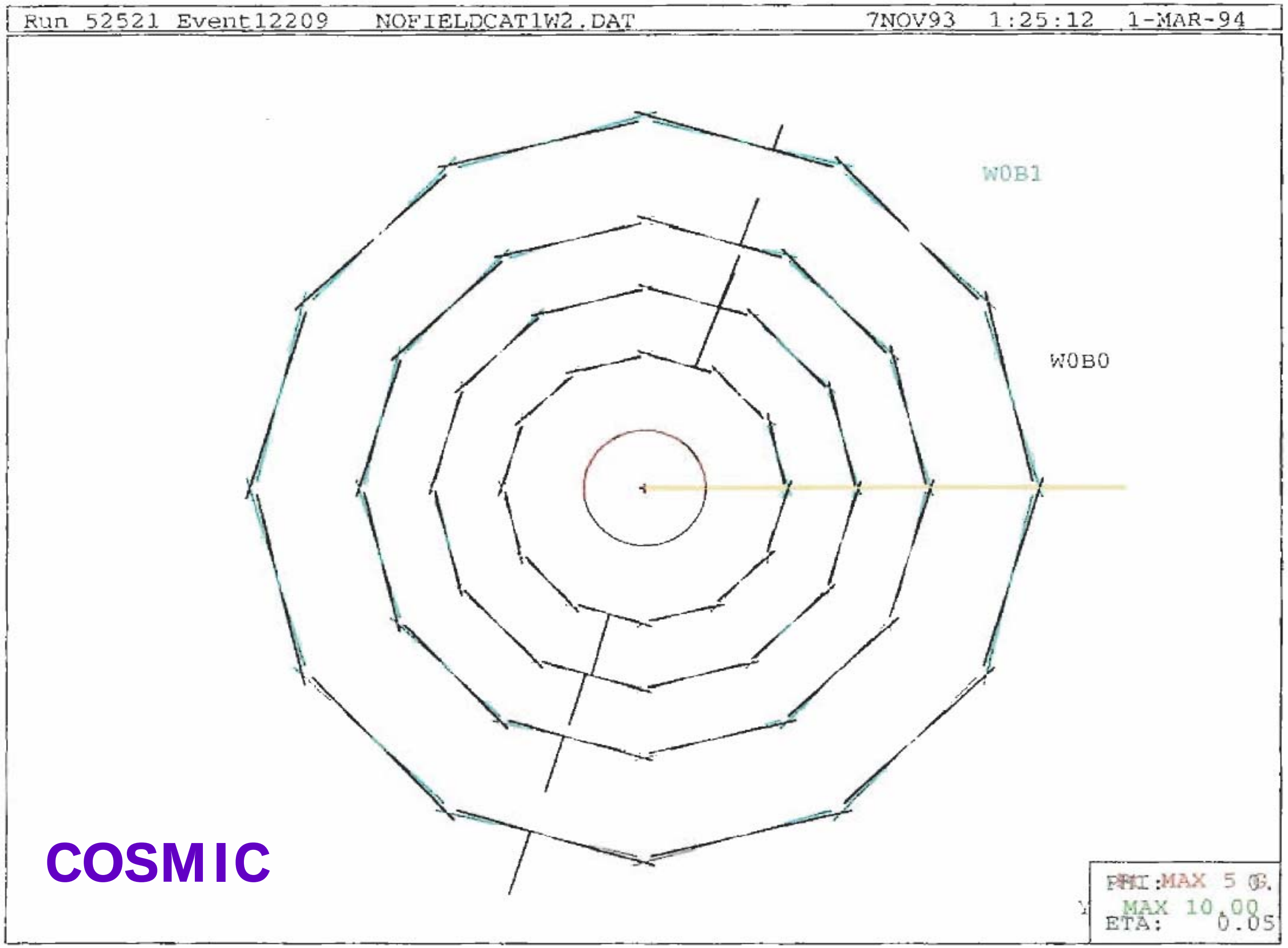
- What about quality control?
- At high production rates, what do you do?
- What we learned w/SVX'
  - Shoot for perfection in assembly:
    - Not because you need a perfect detector
    - It just makes it easier to find problems!
  - Know the source of any problems:
    - Include checks at each step of production to quickly identify the source of any damage that may occur.
  - Keep the pipeline short
    - Modules should be fully tested as soon as possible.
    - Minimize the number of parts at risk

Outcome

SVX' installation completed Oct 8, 1993:
1 day ahead of schedule

All modules worked

Early event displays

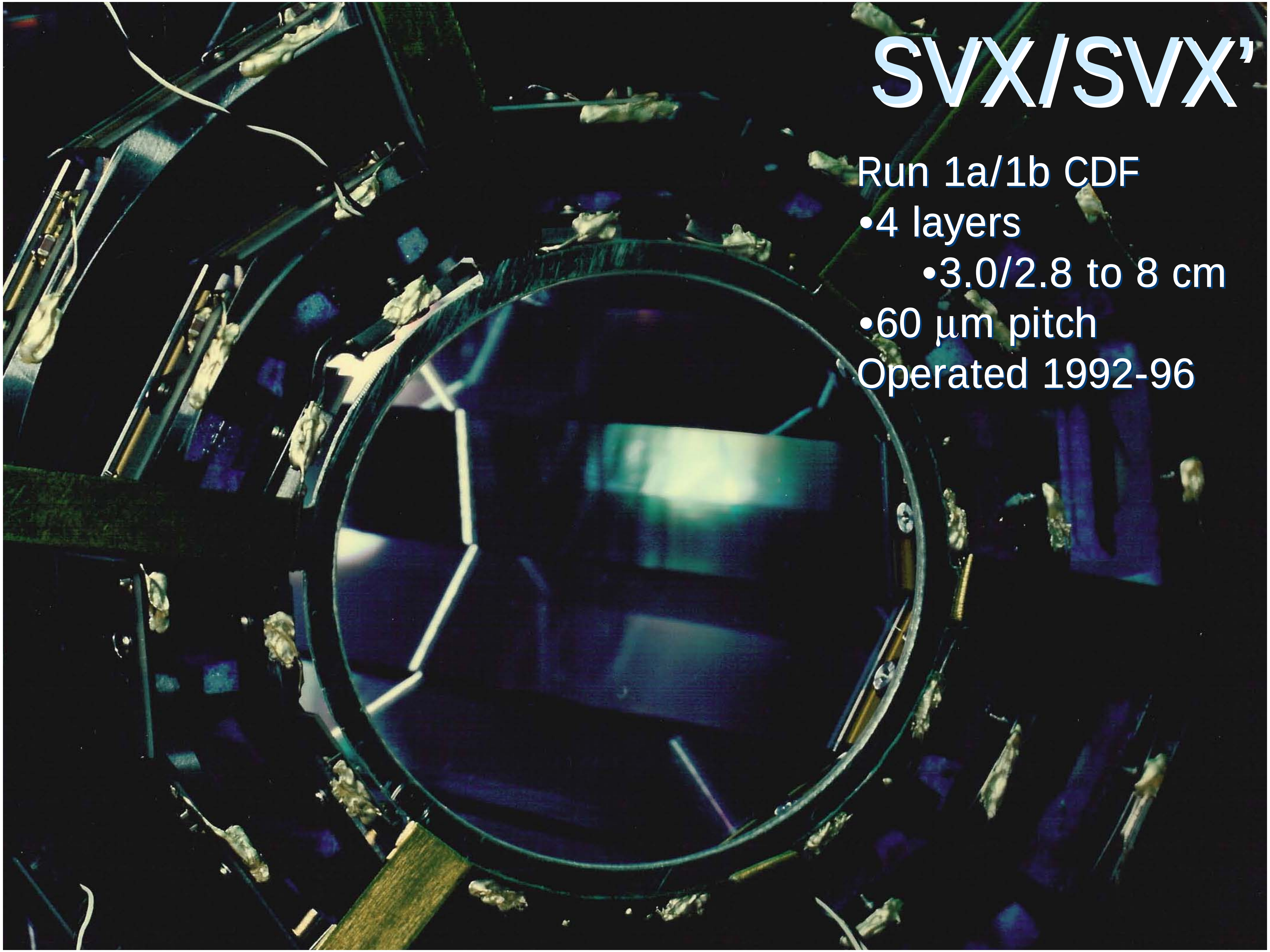


SVX' analysis group

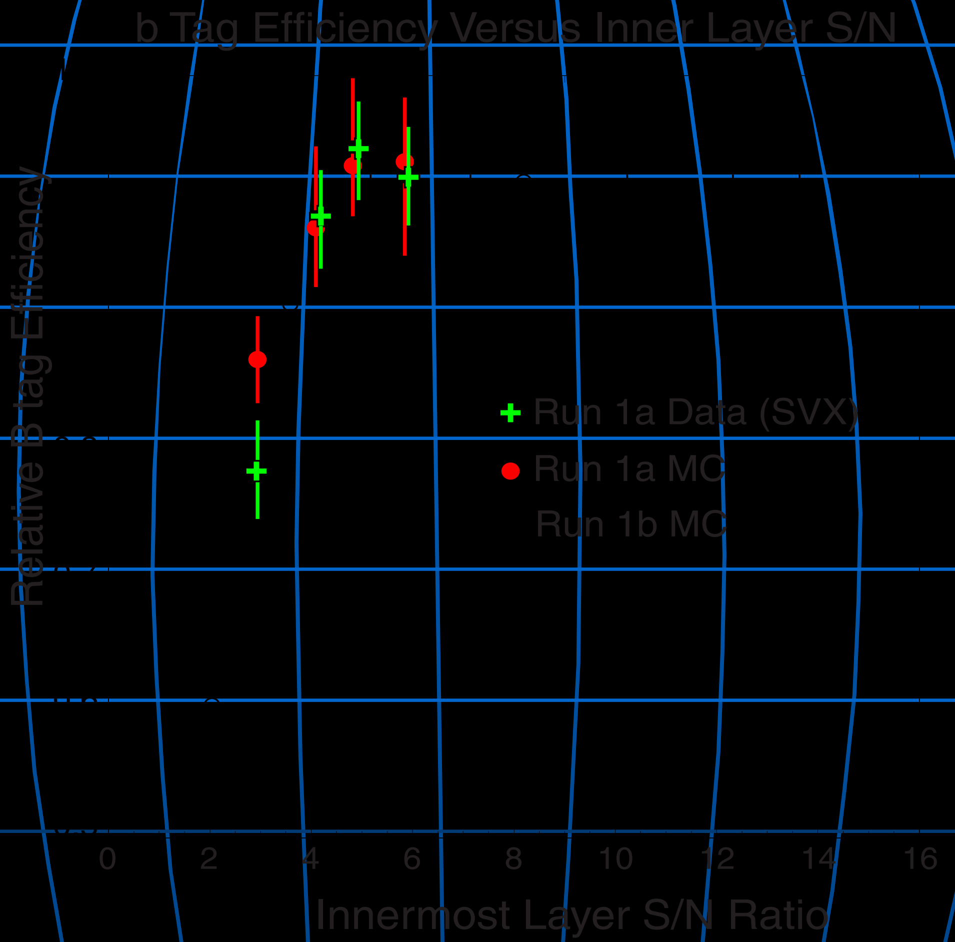
- CDF Run 1b
  - The silicon group had lots of fun thinking about ways to use the detector for physics:
    - *Culbertson, Glenzinski, JI, Shaw, Snider, Stuart, Yao…*
  - Possibly an ideal situation
    - Commissioned and operated it
    - Aligned it
    - Wrote the hit simulation for the CDF Monte Carlo
    - Developed the detailed track selection for b-tagging
    - Invented seed vertex b tagging, optimized it, found a 4.1 σ signal for the top quark !
    - *Measuring M_{top} via the mean b decay length was also an idea from that period - C. Hill recently did it in Run 2*

SVX/SVX’

Run 1a/1b CDF
•4 layers
    •3.0/2.8 to 8 cm
•60 μm pitch
Operated 1992-96

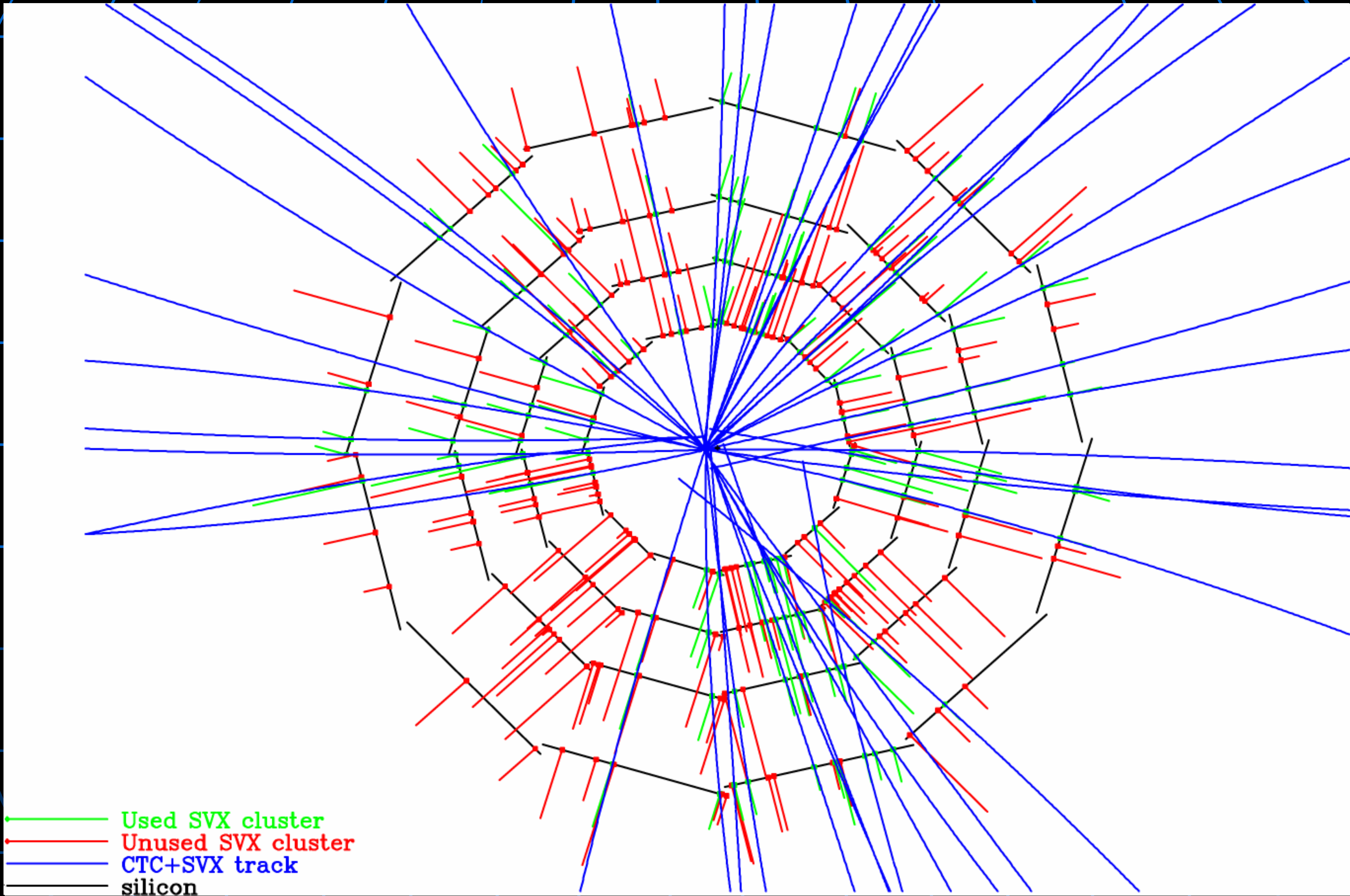


Silicon and B tagging

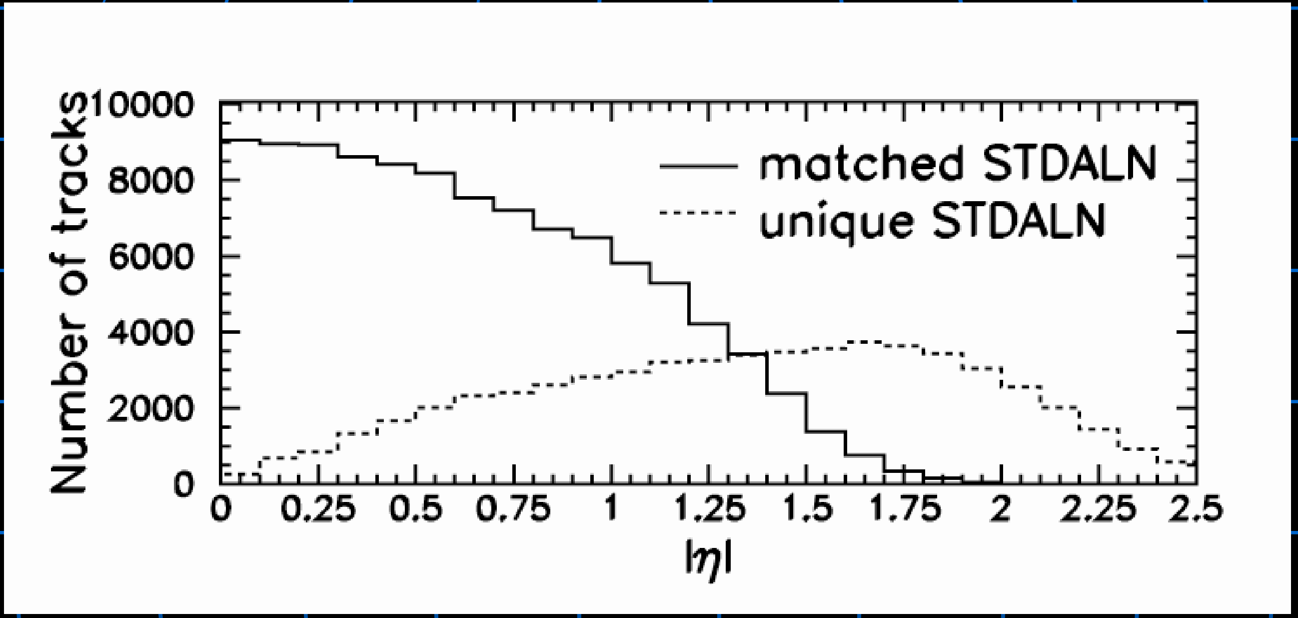


- **The demise of the SVX (Run 1a) taught us that vertex b tagging could even tolerate low S/N on the critical inner layer**

"Standalone" Si Tracking in SVX' c. 1994

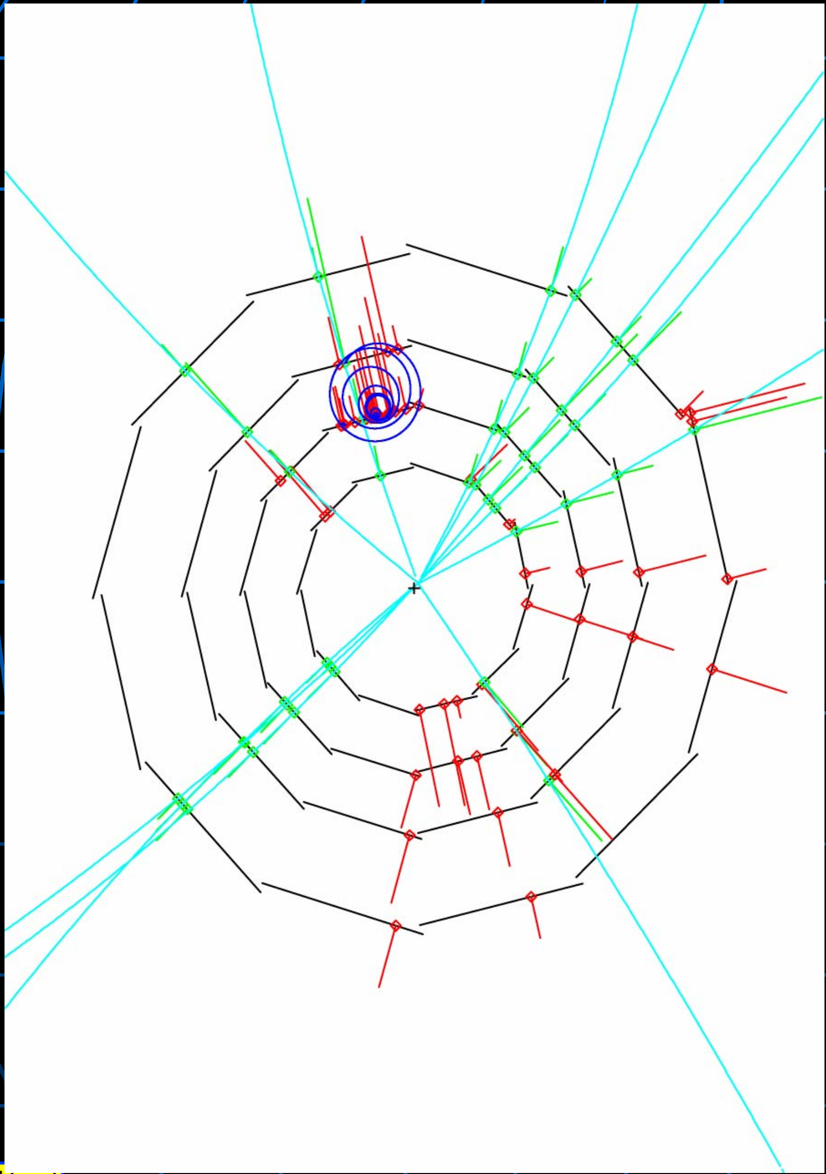


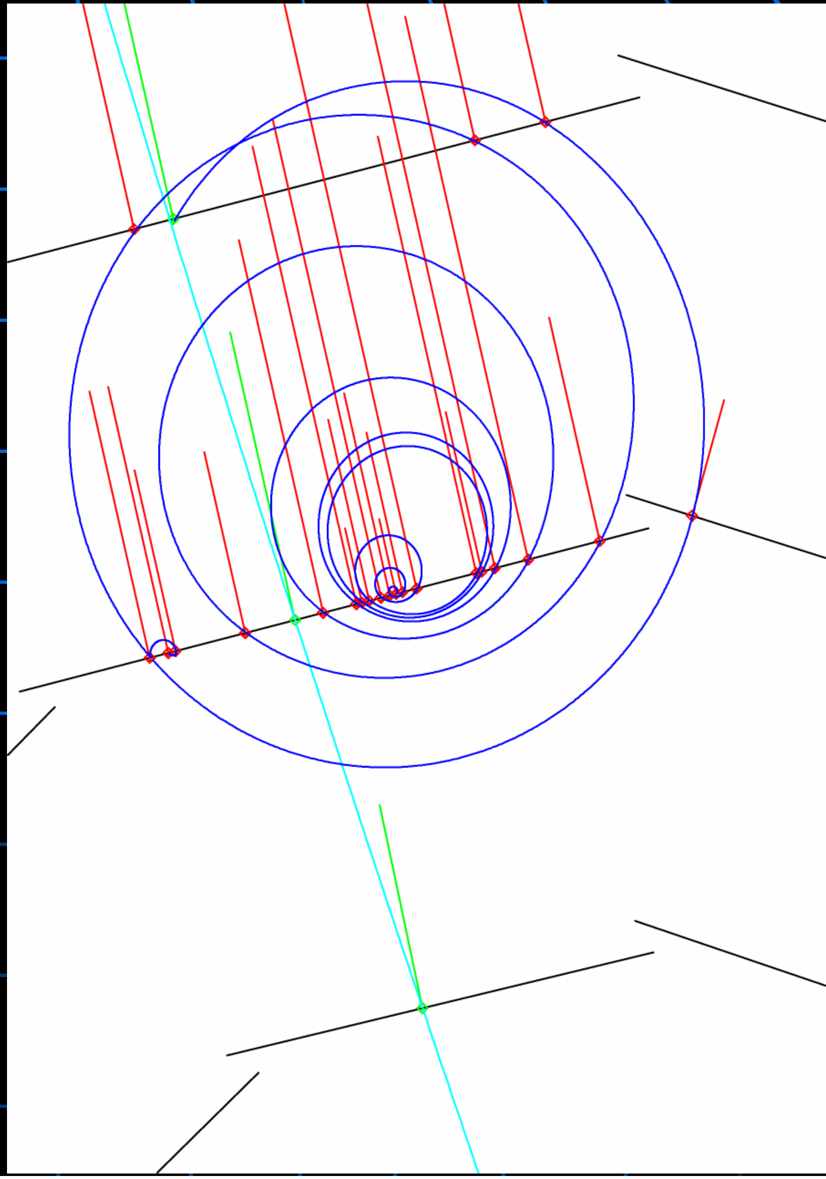
Standalone Tracking With SVX'



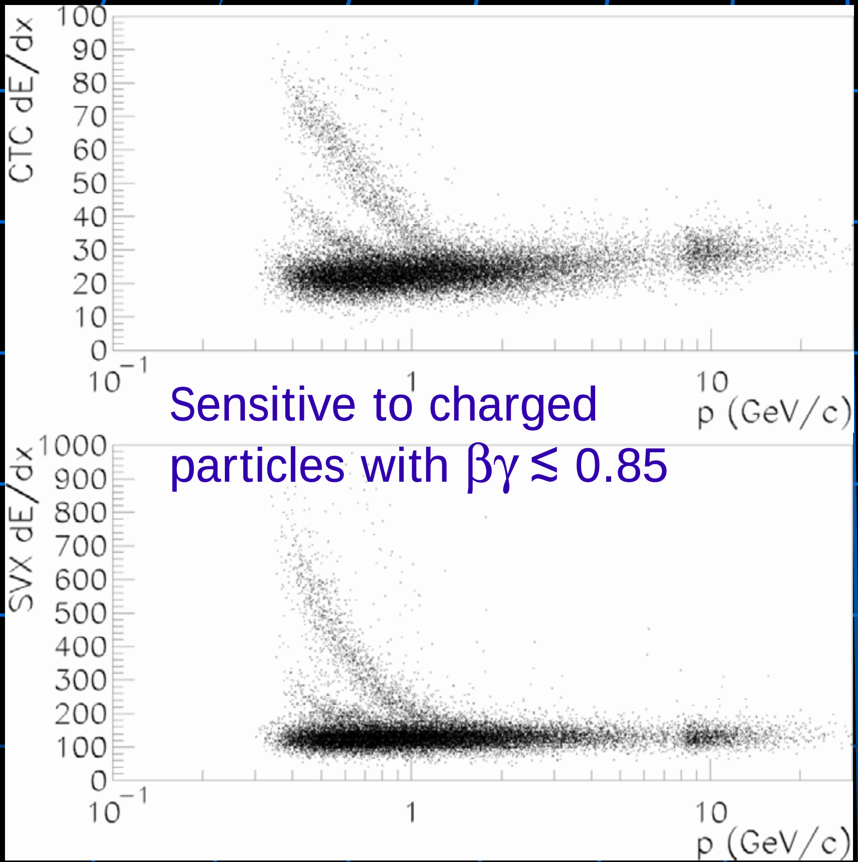
- Most tracks matched to regular tracking
- Those that did not were where you'd expect them
  - SVX' had only axial strips – we used a weighted sum of the charge deposited on 4 layers to measure η
- But… 5 cm lever arm meant poor pt resolution

Delta's in pp collisions

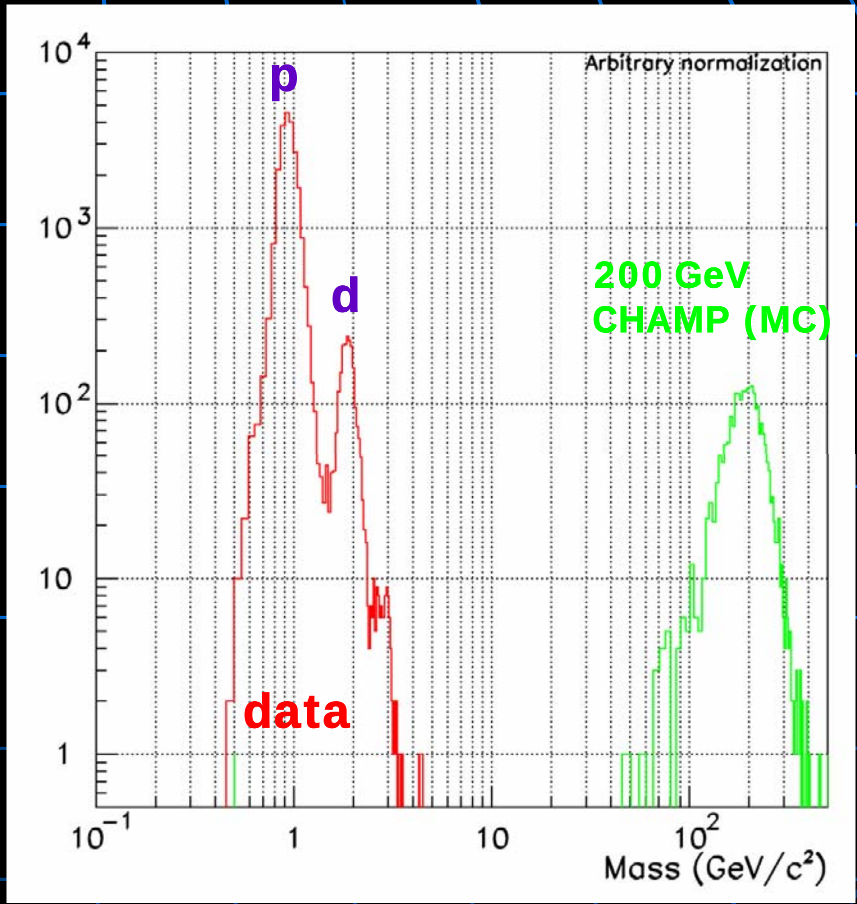




-dE/dx and CHAMPS



Sensitive to charged particles with $\beta\gamma \lesssim 0.85$



SEARCH FOR LONG LIVED CHAMPS

D. Stuart et al. **Phys.Rev.Lett.90:131801**

SVX II (See talk by Tuula Maki)

- Started around same time as SVX' in 1991
- Most challenging CDF silicon detector!
  - *Led by J. Spalding and P. Shepard*

- Sensors: double-sided, many double-metal

- SVX3 chip: Dead-timeless, pipelined, dynamic pedestal subtraction...

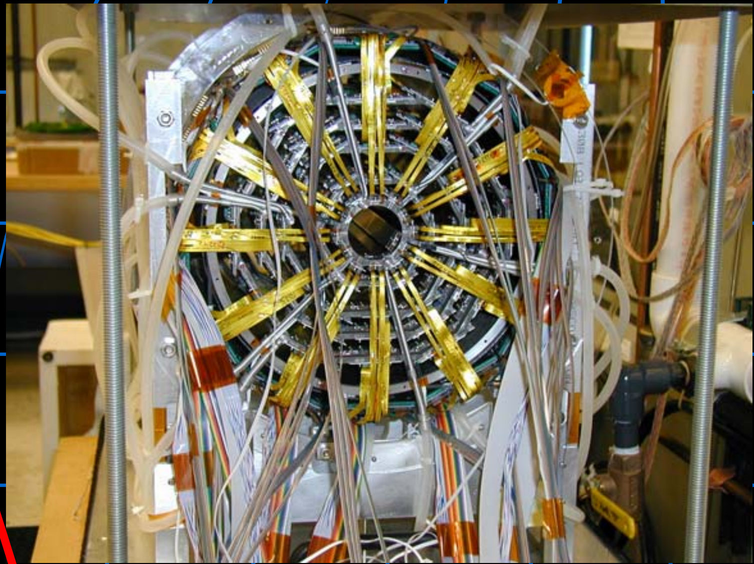
- Mechanics:
  - All strips had to be parallel to beam to within 100 μrad for the online displaced track trigger (SVT)!

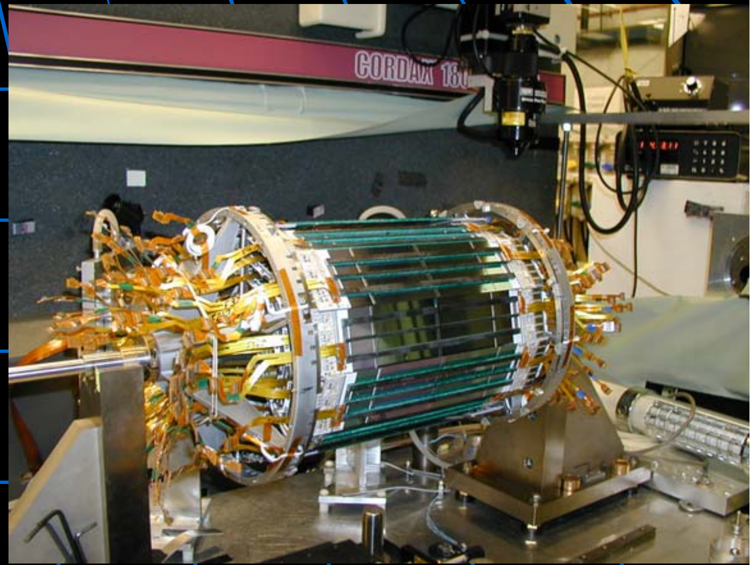
CDF SVX II

3 Barrels: Very Compact design:

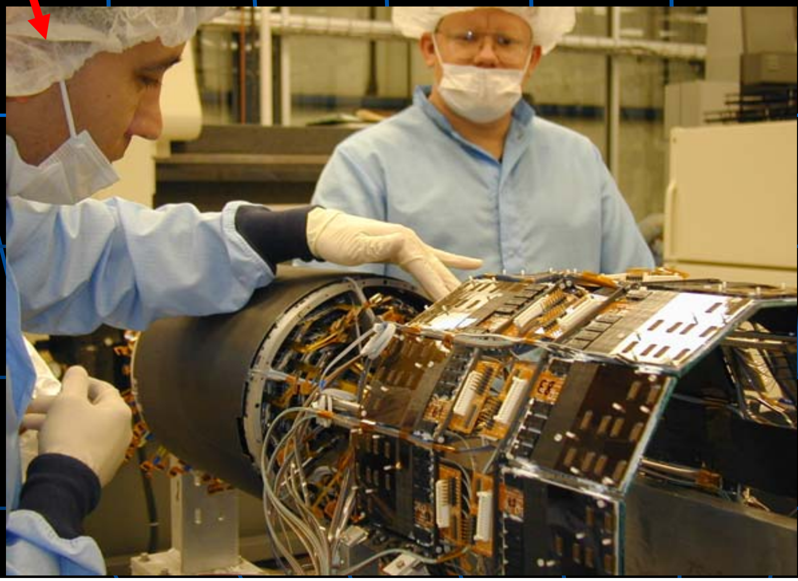
- Electronics mounted on Silicon
- Radial span ~8 cm for 5 layers !

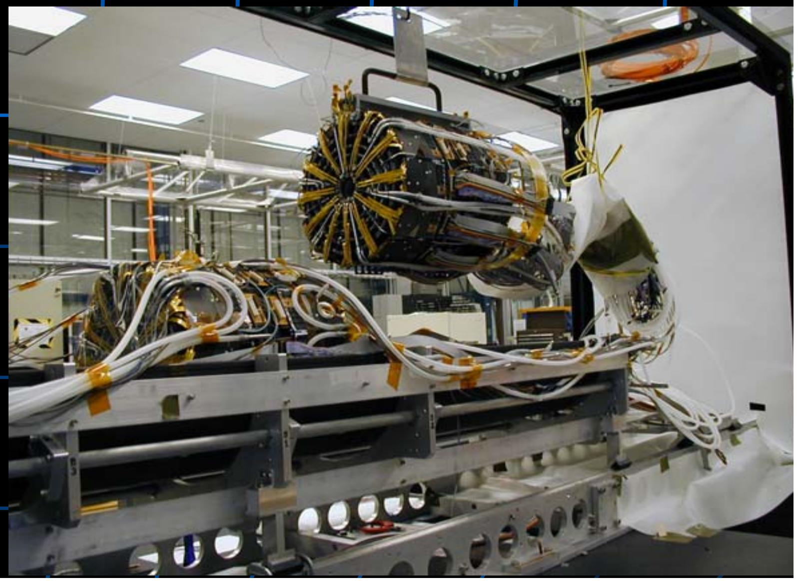
SVXII Barrels





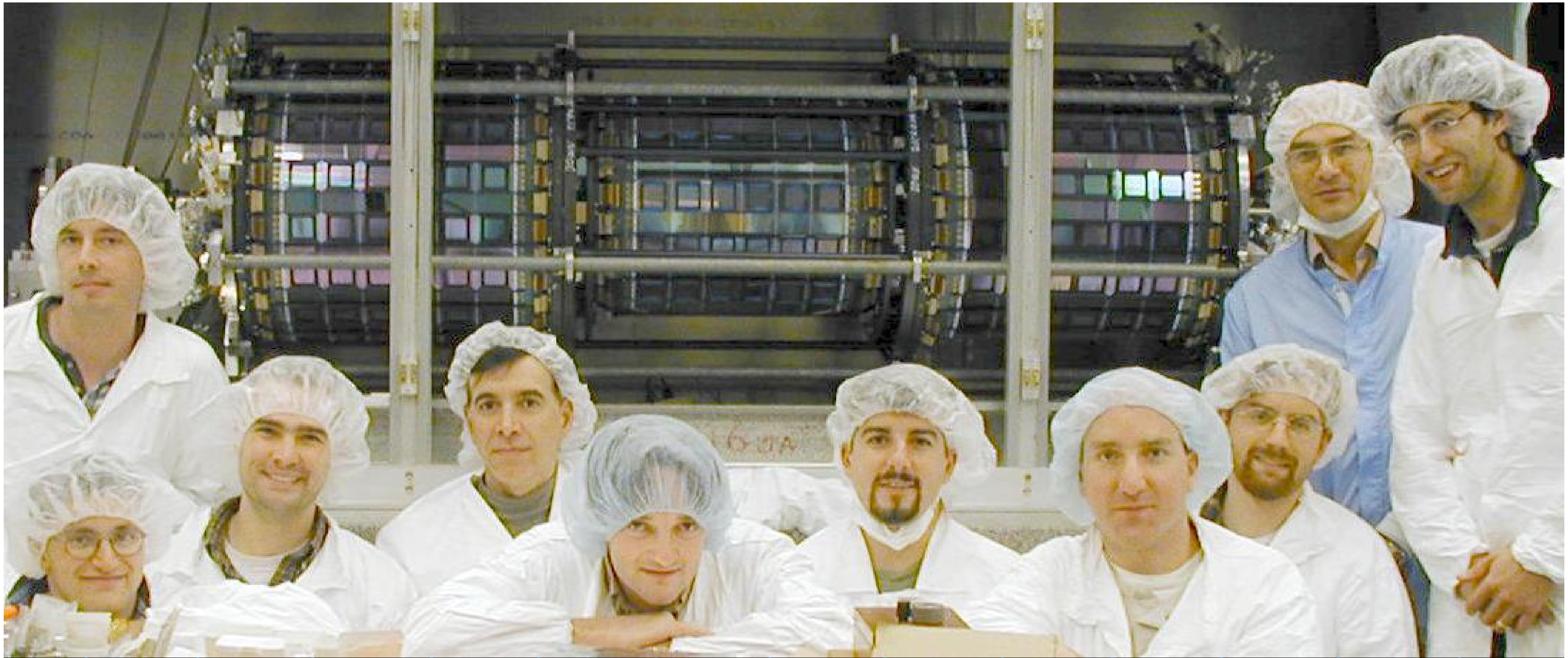
Bert Gonzales and Greg Derylo





ISL

- CDF planned to build a fiber tracker to bridge from the silicon to the outer straw tubes
  - Reviewed in 1996: many concerns
- D. Stuart came up with a way to optimize the readout of a silicon system in this region - made it affordable!!
- JI led an engineering design team and provided all my standalone tracking tools to A. Yagil to study the performance in simulation.
- *We completed a full technical design report in three weeks for what later was called the Intermediate Silicon Layers (ISL)*



- First presentation on ISL design was June 1996
- First DOE review Feb. 1997
- Completed in 2000 *(Above, with much of the group)*

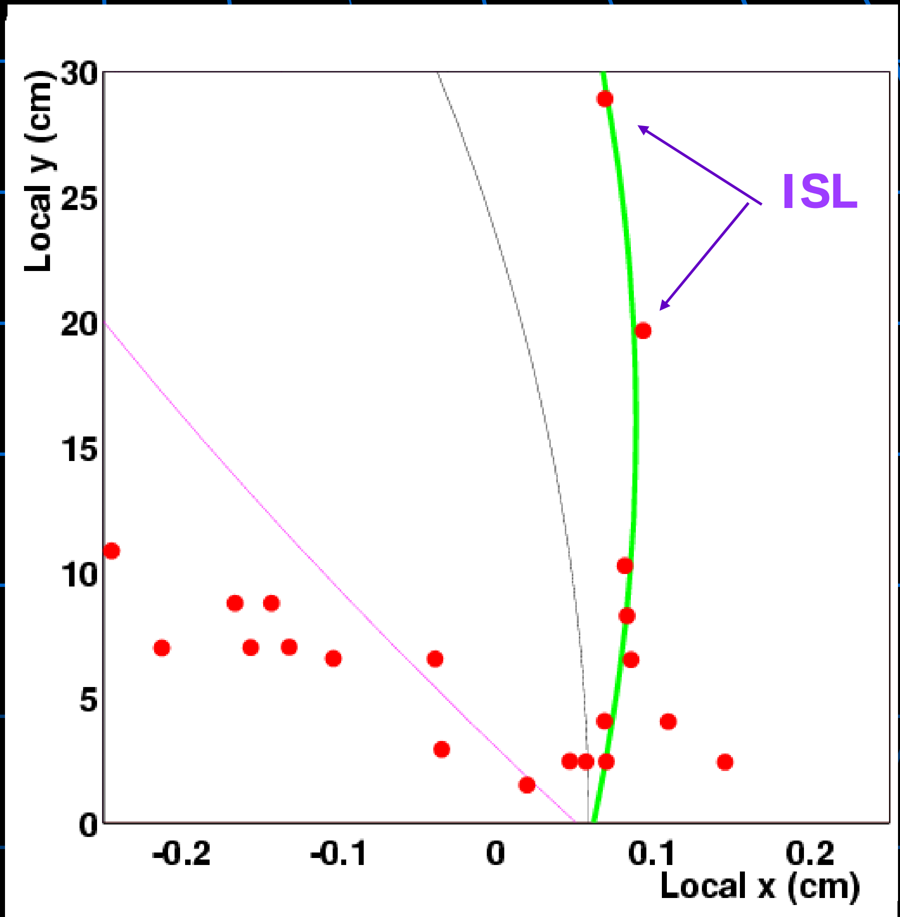
Calorimeter Seeded Silicon Tracking

1. Start with EM calorimeter cluster centroid + primary vertex – Use energy to get curvature
   ⇒2 seed tracks

2. Project into silicon and attach hits using standard pattern recognition

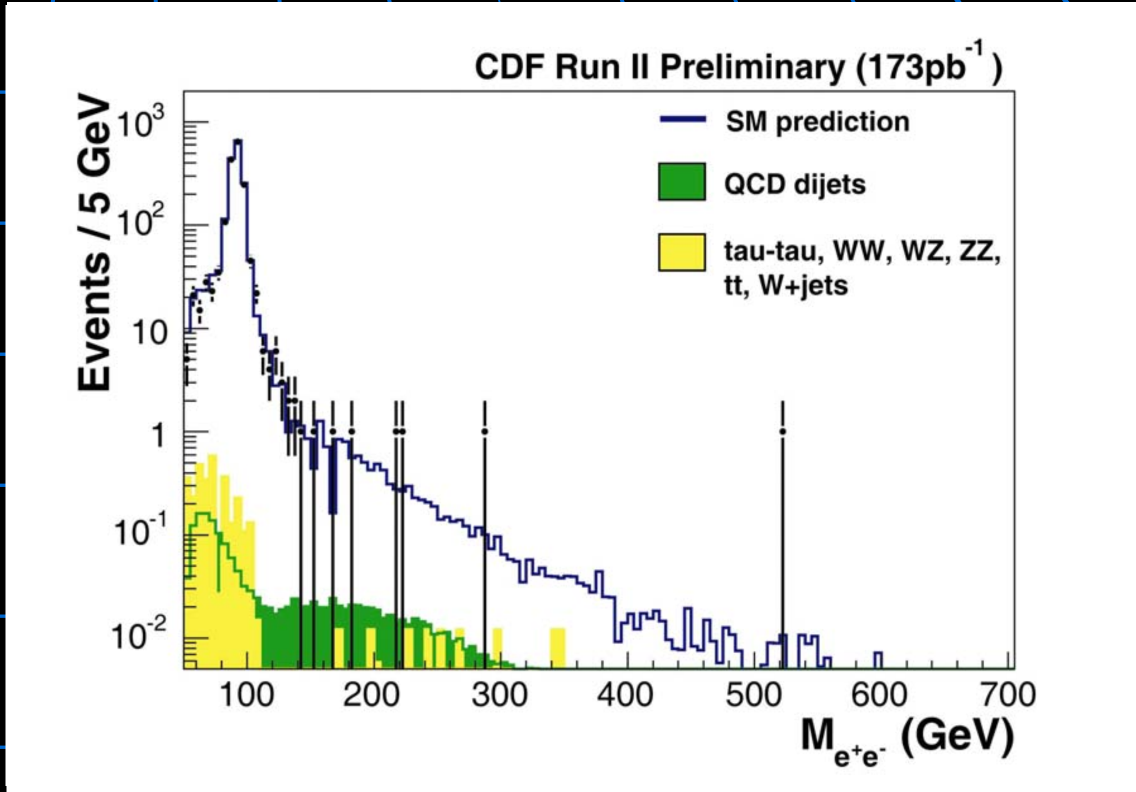
3. Select best χ^2 match and refit

4. When ∃ 1 or 2 ISL hits, result is excellent



Si tracking of forward electrons

- Drell-Yan sample with both EM clusters forward (no drift chamber tracking)
- One leg with Silicon tracking
- Two legs with Silicon tracking



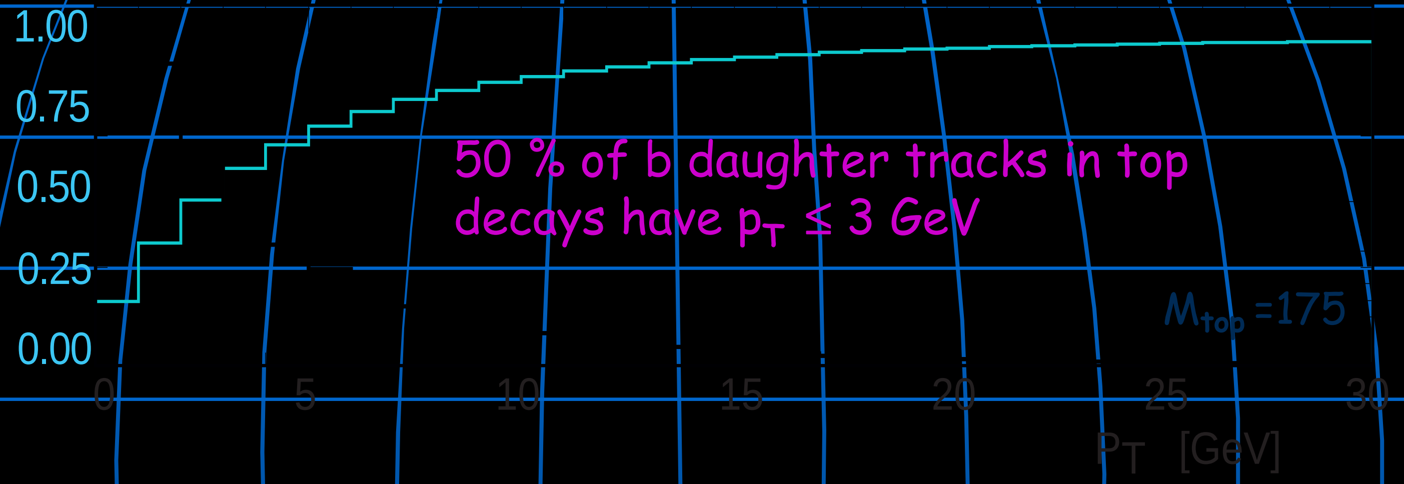
Forward lepton id increases the acceptance for multi-leptonic final states. (D. Stuart, T. Nelson, C. Issever et al.)

Run 2 Sensors

- CDF and DZero sensors were a major effort
  - Double-sided, double metal etc.
- Micron
  - Had ~5-6 CDF/D0 people full-time at Micron
- HPK
  - They also had some trouble:

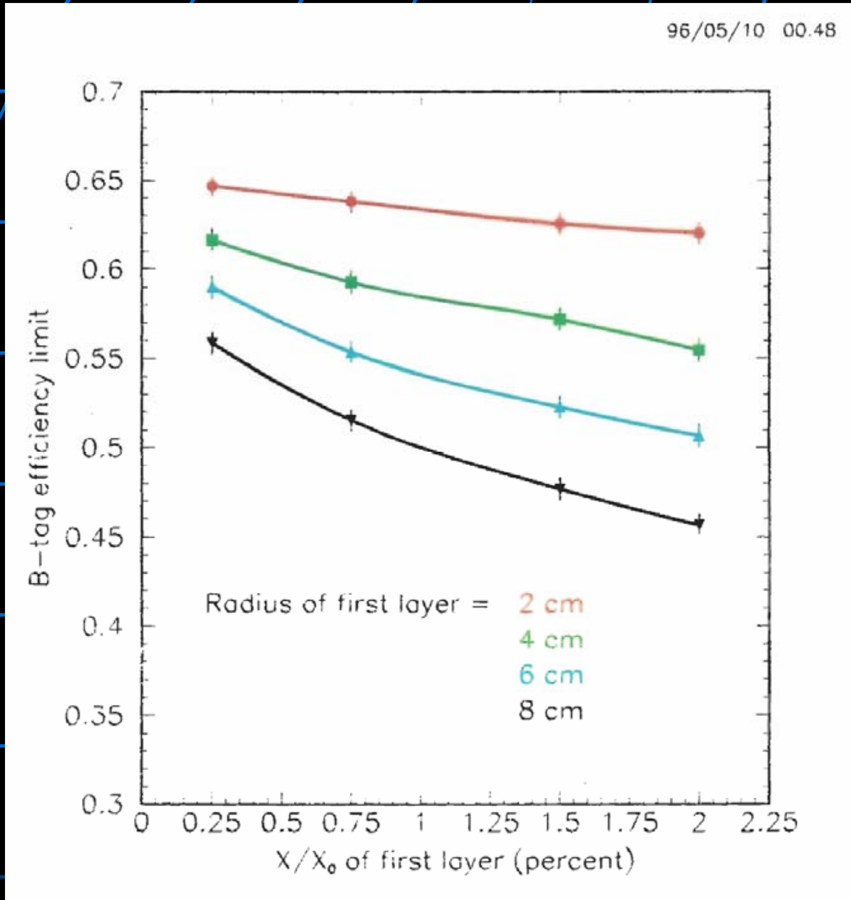
"We will finish your order, but we will not make double-sided sensors again." Yamamoto

B tagging



- Even for b jets in top decays, low p_T is key:
  - Threshold of 500 MeV was important in CDF
- SVX II had lots of material (front end electronics) on the innermost layer
  - low momentum tracks would be poorly resolved

Material and Radius



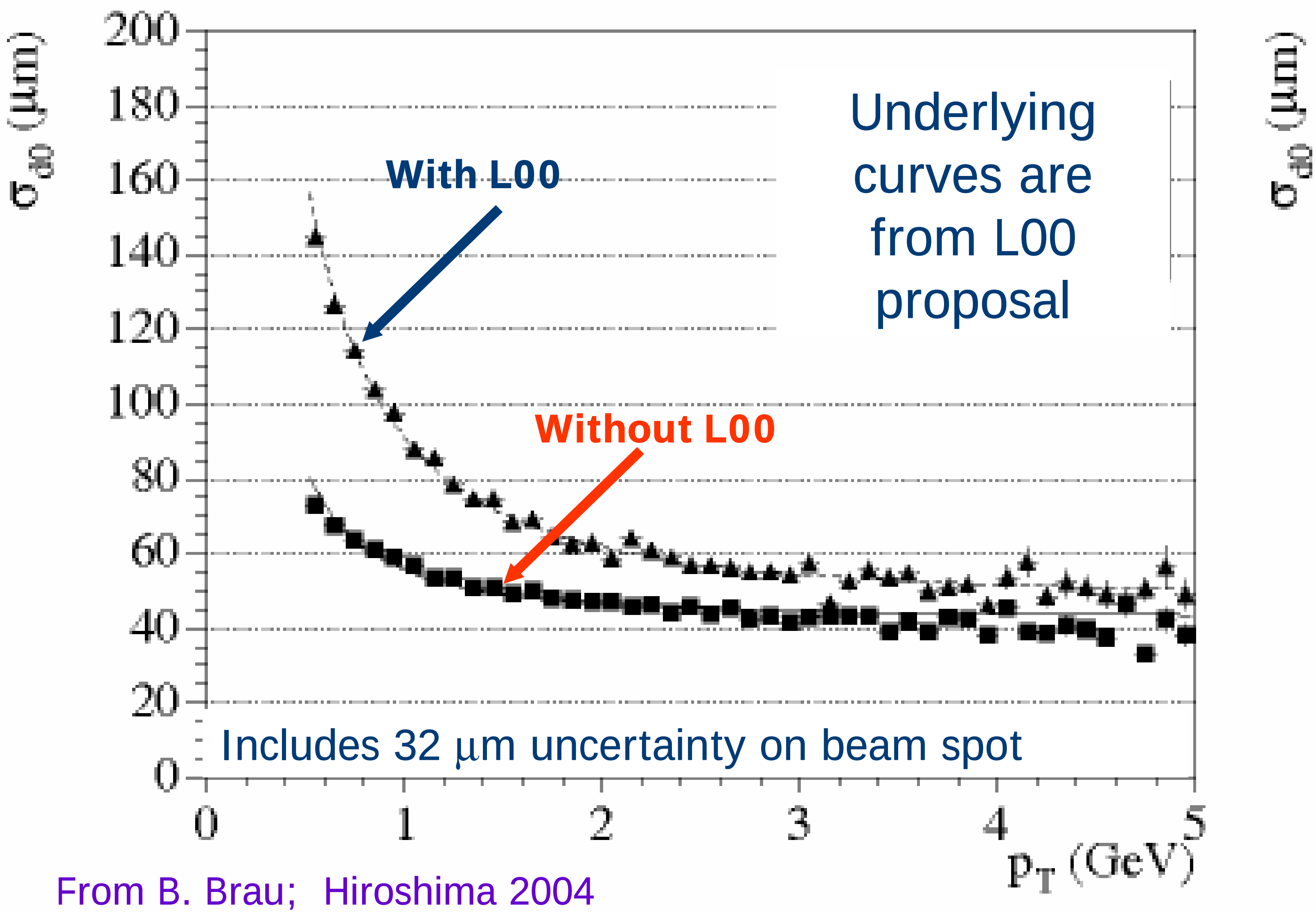
- Material effect on b tagging
  - depends a lot on 1st layer radius
  - below about 2 cm, it starts not to matter very much
- Combine this with:
  - UA2 experience with silicon on beam pipe and
  - LHC radiation hard detectors

…And Voila' Layer 00: A layer of silicon strips right on the beam pipe

"How do you fix a problem of too much material by adding more material?"

– L. Nodulman at the very first Layer 00 presentation: Dec. 9, 1997

Silicon on the beam pipe: Layer 00

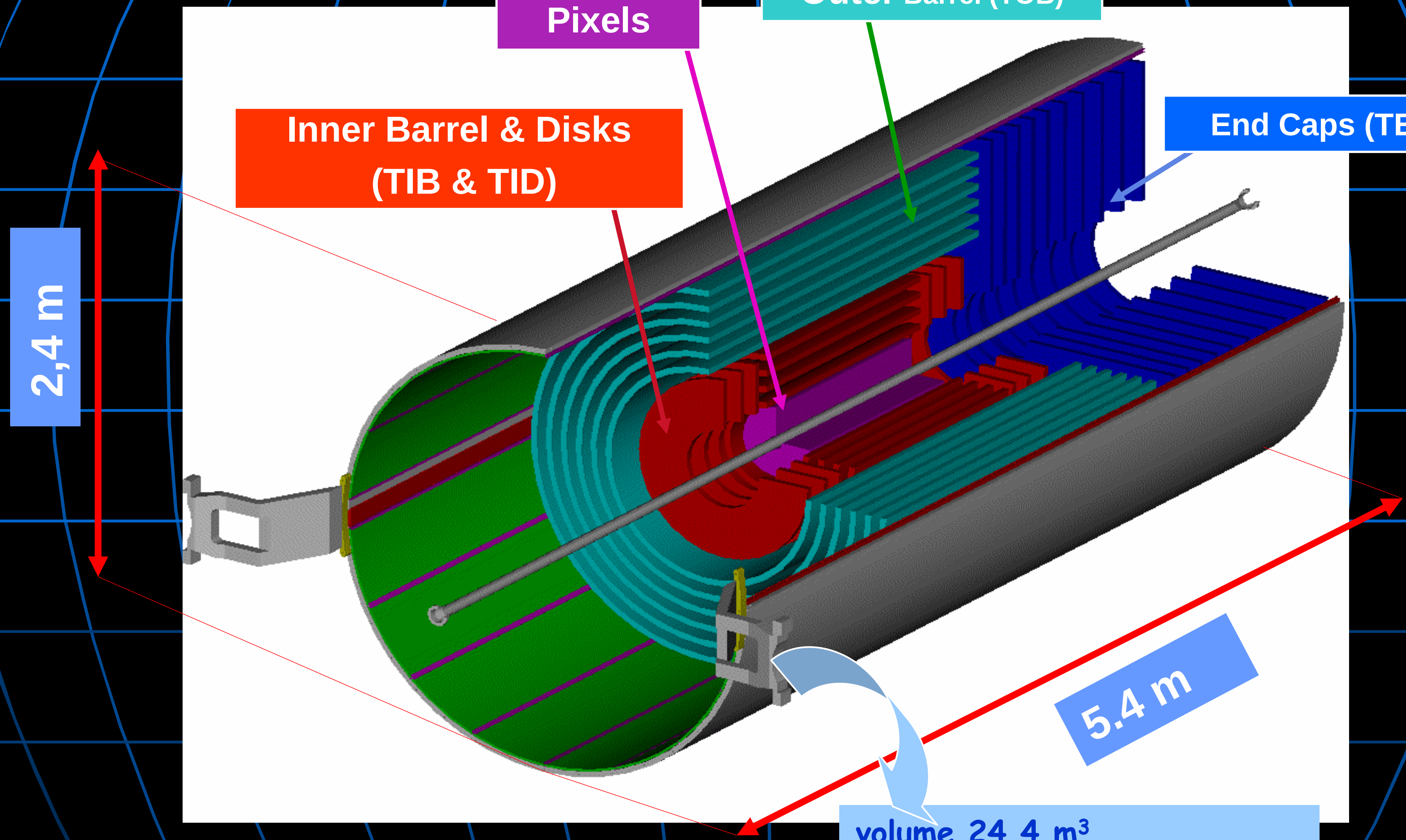


From B. Brau; Hiroshima 2004

CMS: Finally An All Silicon Tracker*

- CMS decided to build an all silicon tracker ~2000
  - Technical and financial concerns for MSGCs
  - Cost for a silicon tracker had fallen
- US activity
  - 1997-1999: planned to build ~5 m^2 modules
    - *There was a CDF ISL connection …*
  - This ultimately grew to ~130 m^2
  - (C. Civinini and K. Klein will discuss the CMS tracker in more detail.)

CMS All Silicon Tracker



volume 24.4 m^3
running temperature – 20 ^{0}C

Some Scary Numbers

10,000,000 individual strips

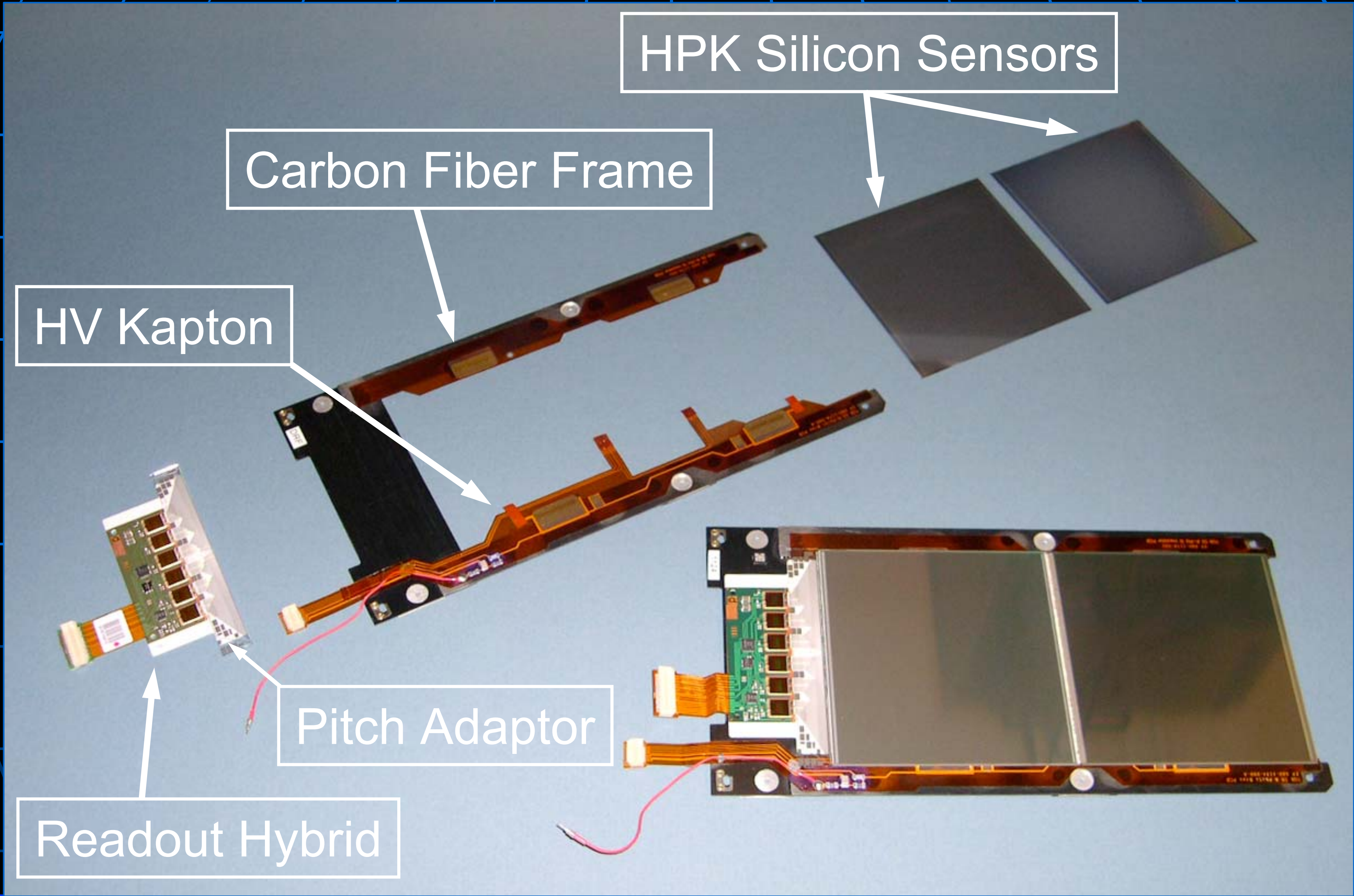
78,000 APV readout chips

26,000,000 individual wirebond wires !

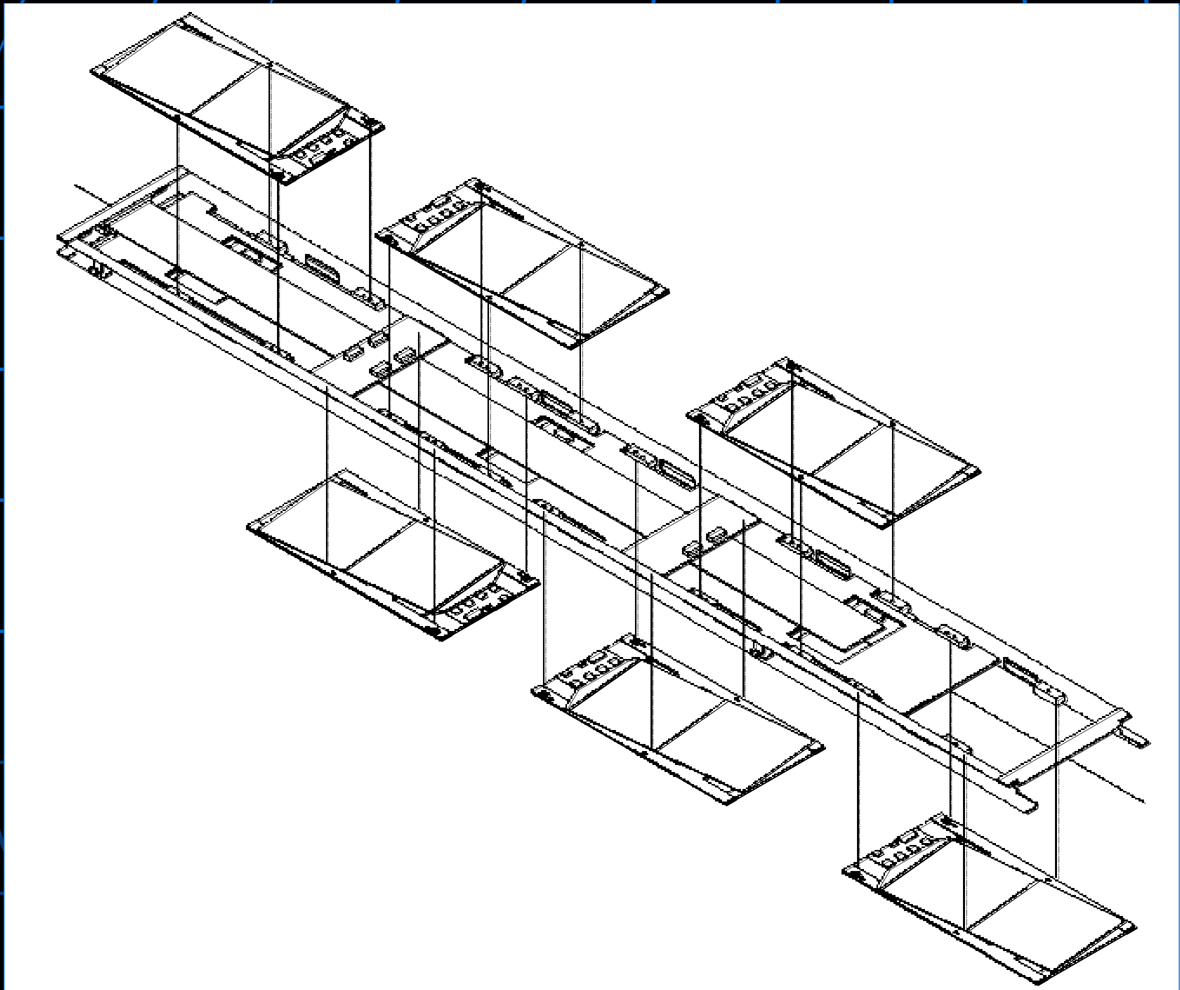
207 m^2 of silicon installed

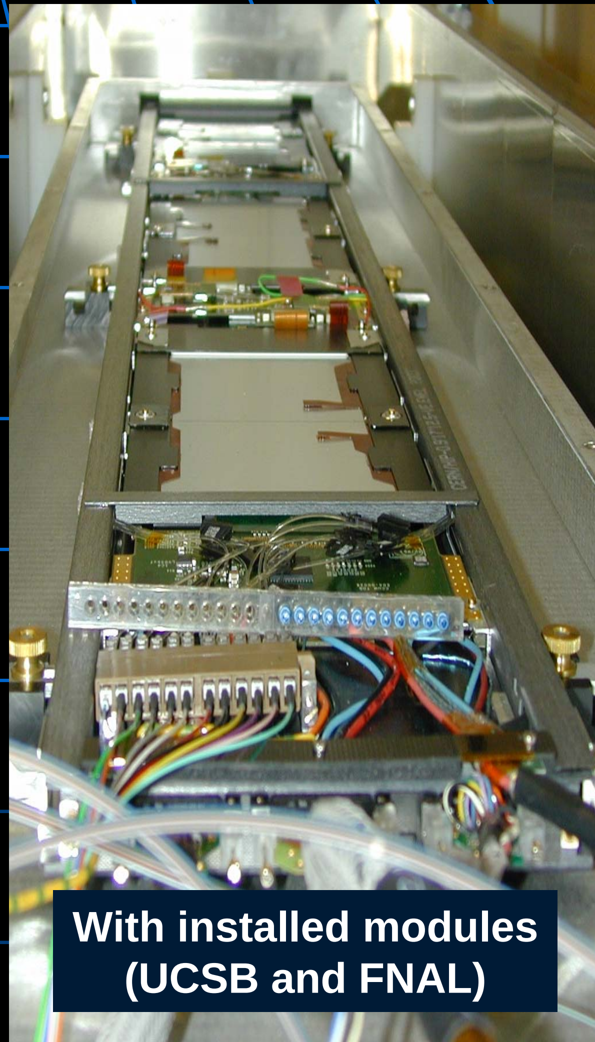
100 kg of Silicon!

Simple Modules



Rods

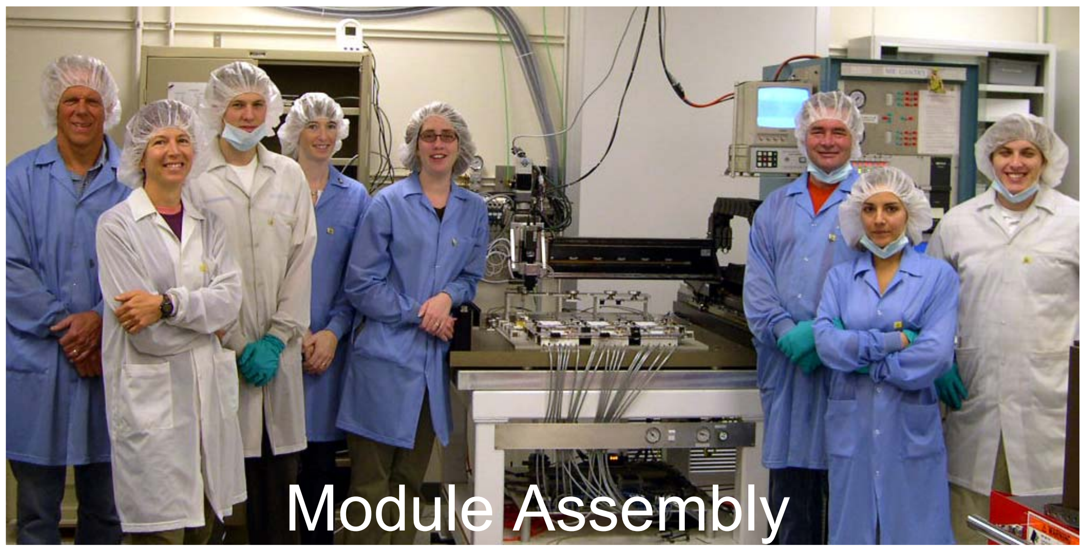




With installed modules (UCSB and FNAL)

Modules are mounted on support structures with integrated cooling, electronics

Santa Barbara Production Crew


Module Assembly


Wire Bonding


Hybrid/Module Testing


Rod Assembly/Testing

Can a small university group build ~75 m^2 Si detectors ?

- Simple robust designs
- Detailed procedures and logistical plans
- Automation
  - Assembly
  - Wire-bonding
  - Testing

- But most of all: Great People!

Preparations

- Studied and then improved production work flow
- Analyzed failure modes of all systems
  - Find whatever can interrupt production: Acquire spares
- Cross-train technicians
  - All persons with critical tasks must have backups
- Detailed written procedures for *every* task
  - Specific training required.
  - Lines of responsibility established.
  - A list of ~25 procedures can be found at:

    http://hep.ucsb.edu/cms/cms_procedures

Production Cycle


Wire bond hybrid

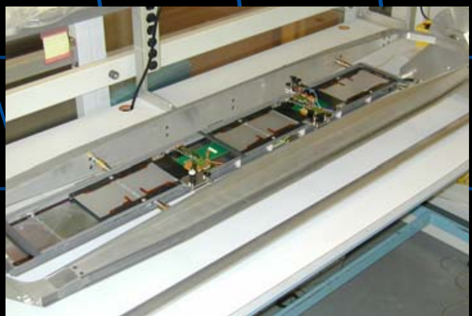

Thermal test hybrids


Assemble modules


Wire bond module


Test bonded module


Thermal test module

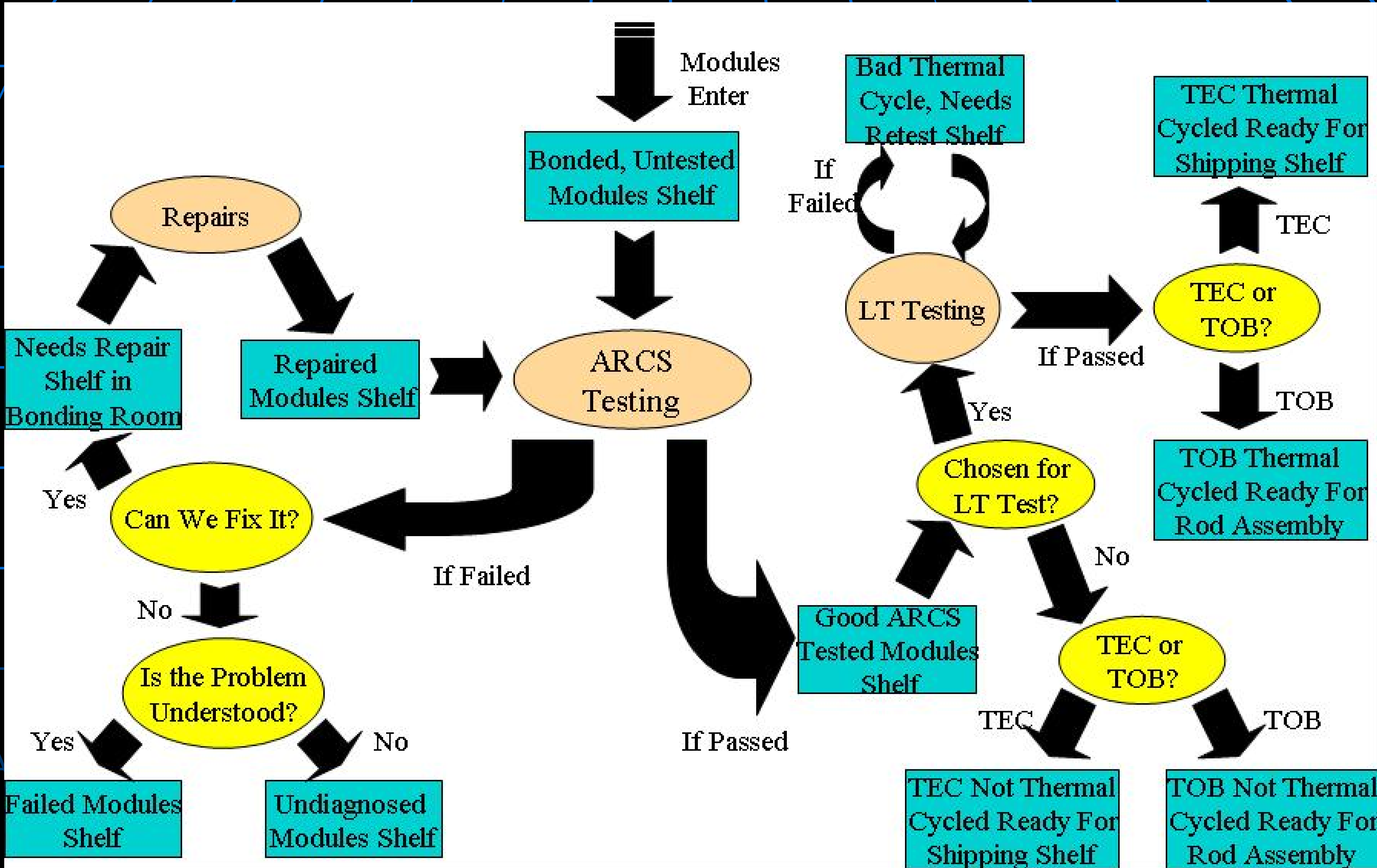

Assemble rods


Single rod test


Long-term
Thermal test

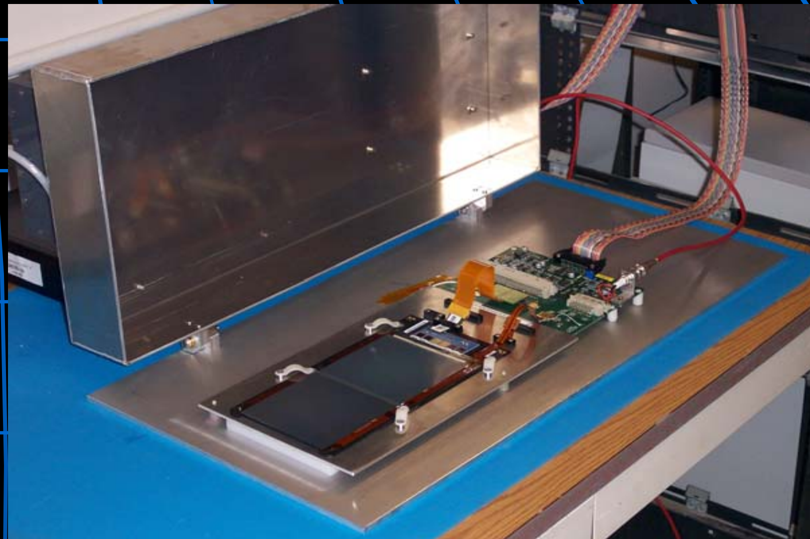

Ship to CERN

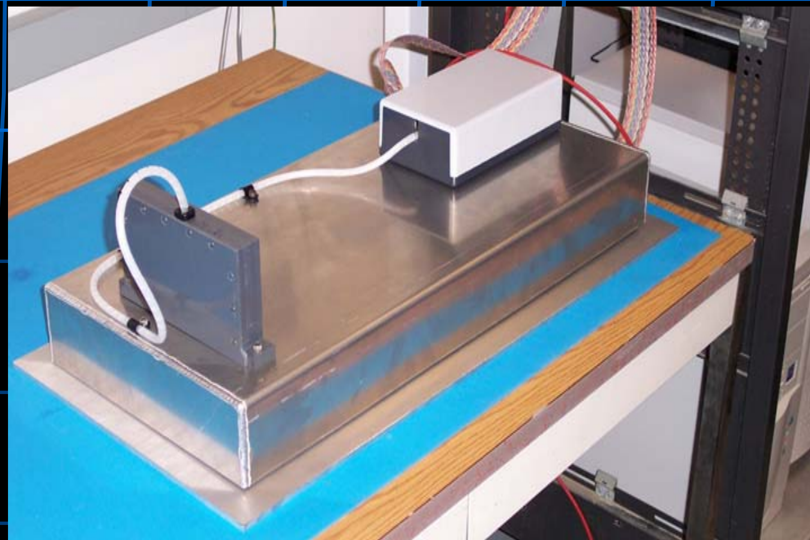
Module Testing: Example of a Flow Plan



Module Testing

- Developed fixtures to obtain minimum noise
- Maximum sensitivity
- Automated Fault finding

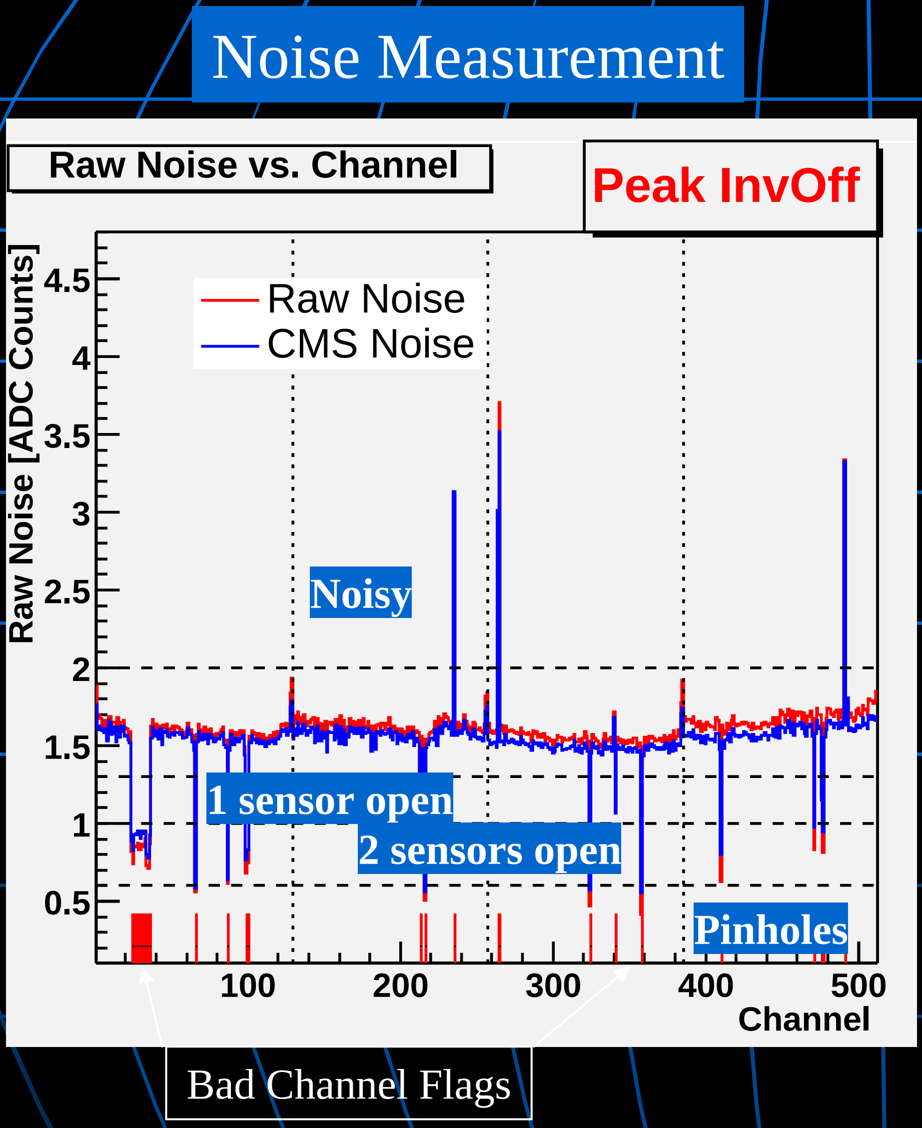




Systems Failure Analysis

- Find all weaknesses and have contingency plans.
  - We had less than 3 days downtime due to equipment failure on any stand.

Clear, robust fault signatures



Faults identified quickly for feed-back to the production line (i.e. the short pipeline rule).

Use results of many partially correlated tests to determine the type and location of faults

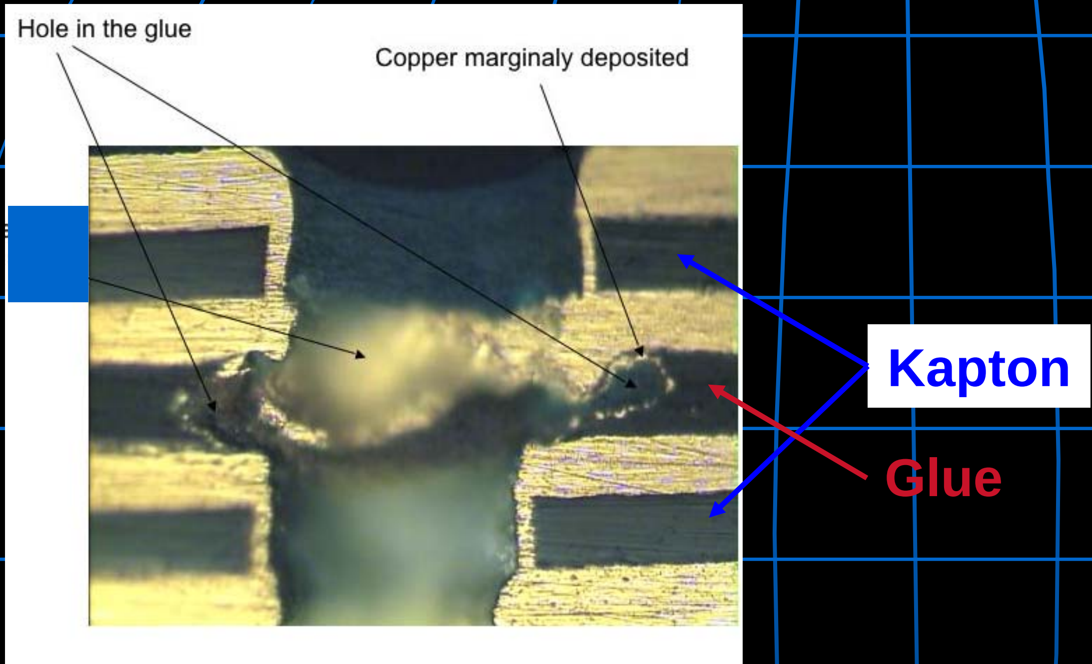
>99.9% faults are found with <0.01% error rate

Quality Assurance

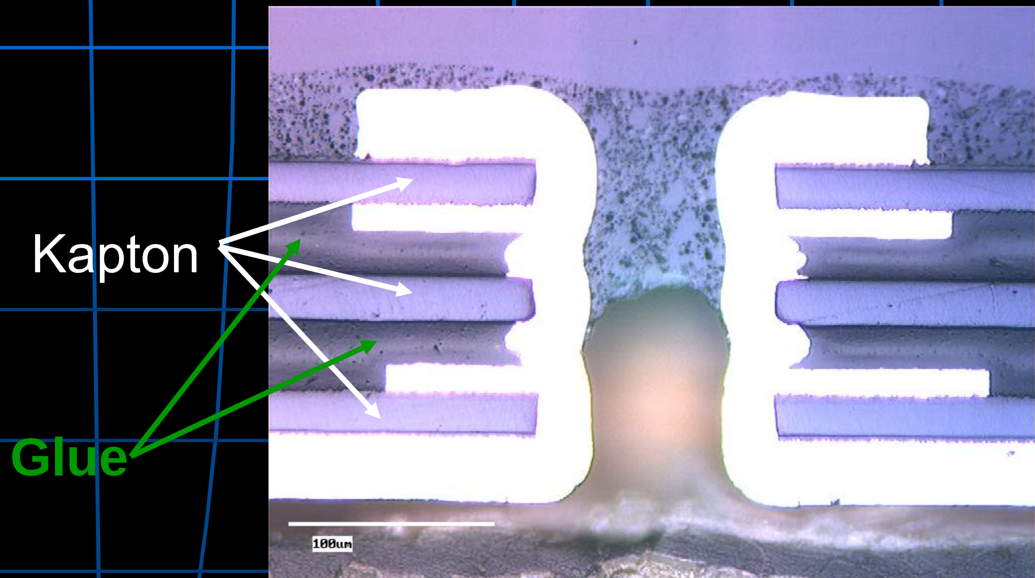
- Using the methods learned in CDF we found a number of potentially serious flaws:
  - Common Mode Noise (CMN) in ST sensors (TOB & TEC)
    - >12,000 sensors to Hamamatsu Corporation
  - Broken traces on hybrid pigtails: (TIB, TOB & TEC)
    - integrate the pigtail into the kapton layers.
  - Poorly plated vias: (TIB, TOB & TEC)
    - change hybrid production methodology and QA.
  - Degradation of Ag epoxy bias connection. (TOB & TEC)
    - bias connection made with wirebonds.
  - I2C communication failures on rods: (TOB & TEC)
    - Redesign interconnect cards.
  - Sensor damage due to discharge: (TOB,TEC)
    - Resolved by encapsulating and modifying power supplies.

- After all problems were solved, we finally started production. Currently we are in the miraculous recovery stage...

Hybrid Via Opens



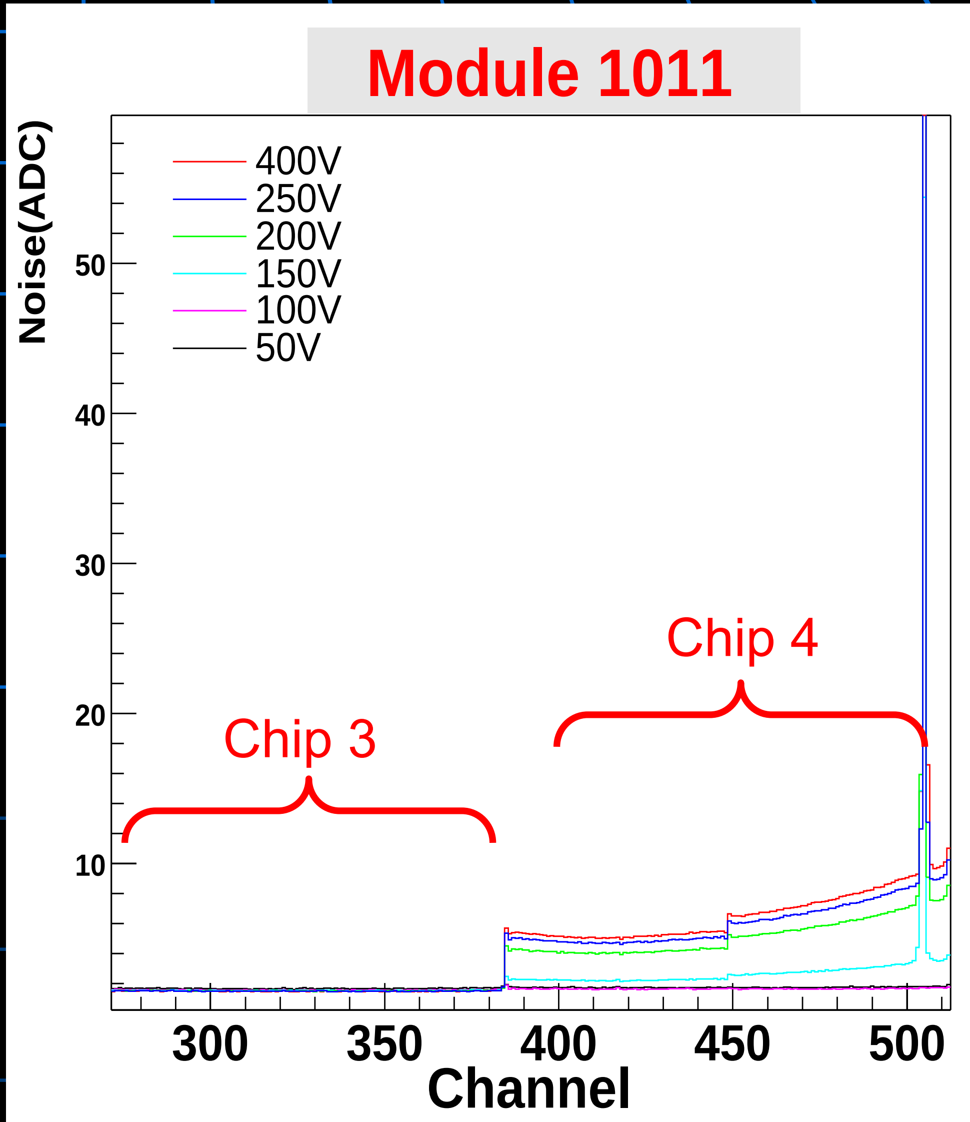
- Opens in the power vias appeared with time
  - Inconsistently plated



- Fixed by better drilling and adding an intermediate kapton layer

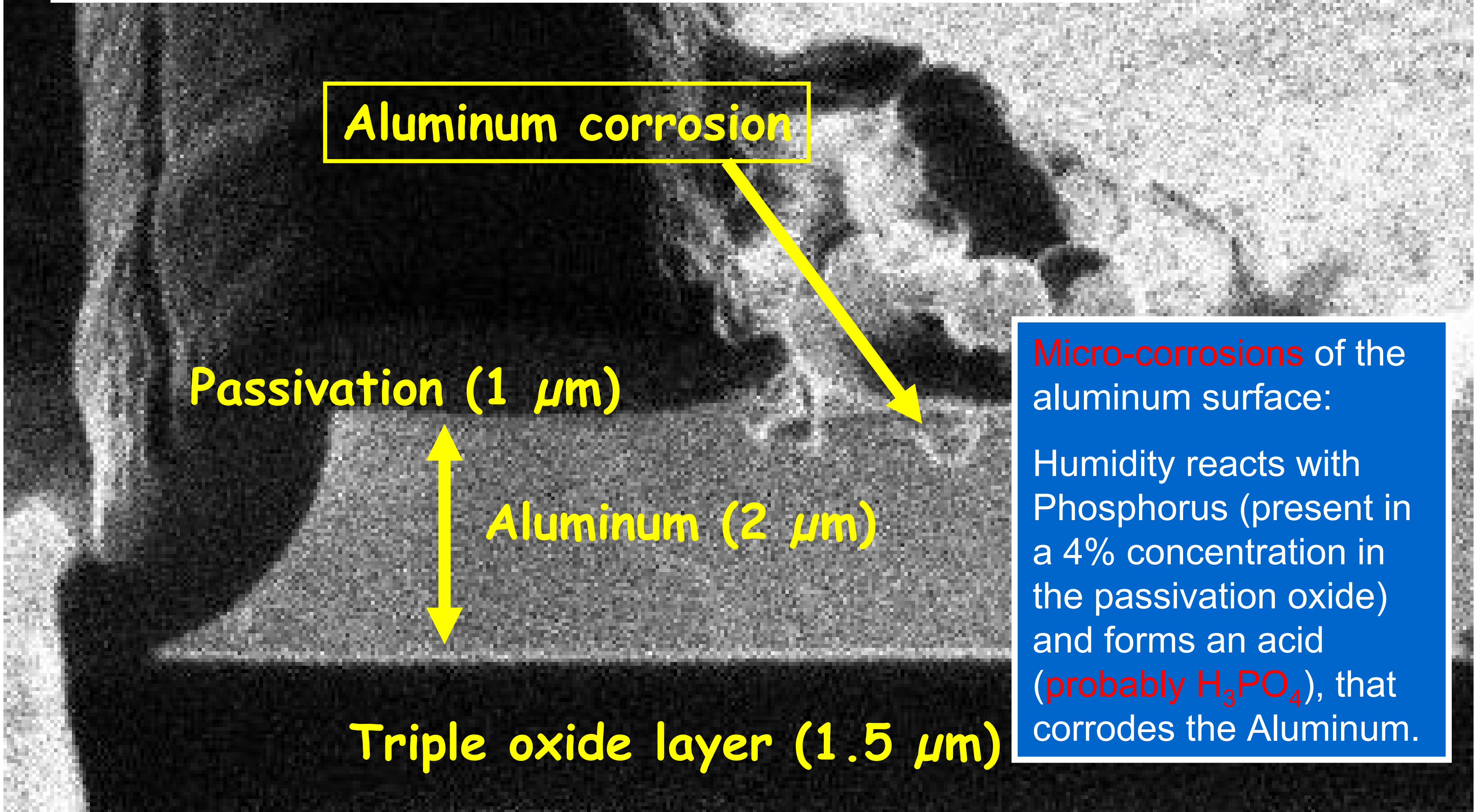
Common mode noise (CMN)

- A fraction of modules with STM sensors showed CMN
  - Correlates with 1-2 very noisy channels
  - Source: micro-discharge



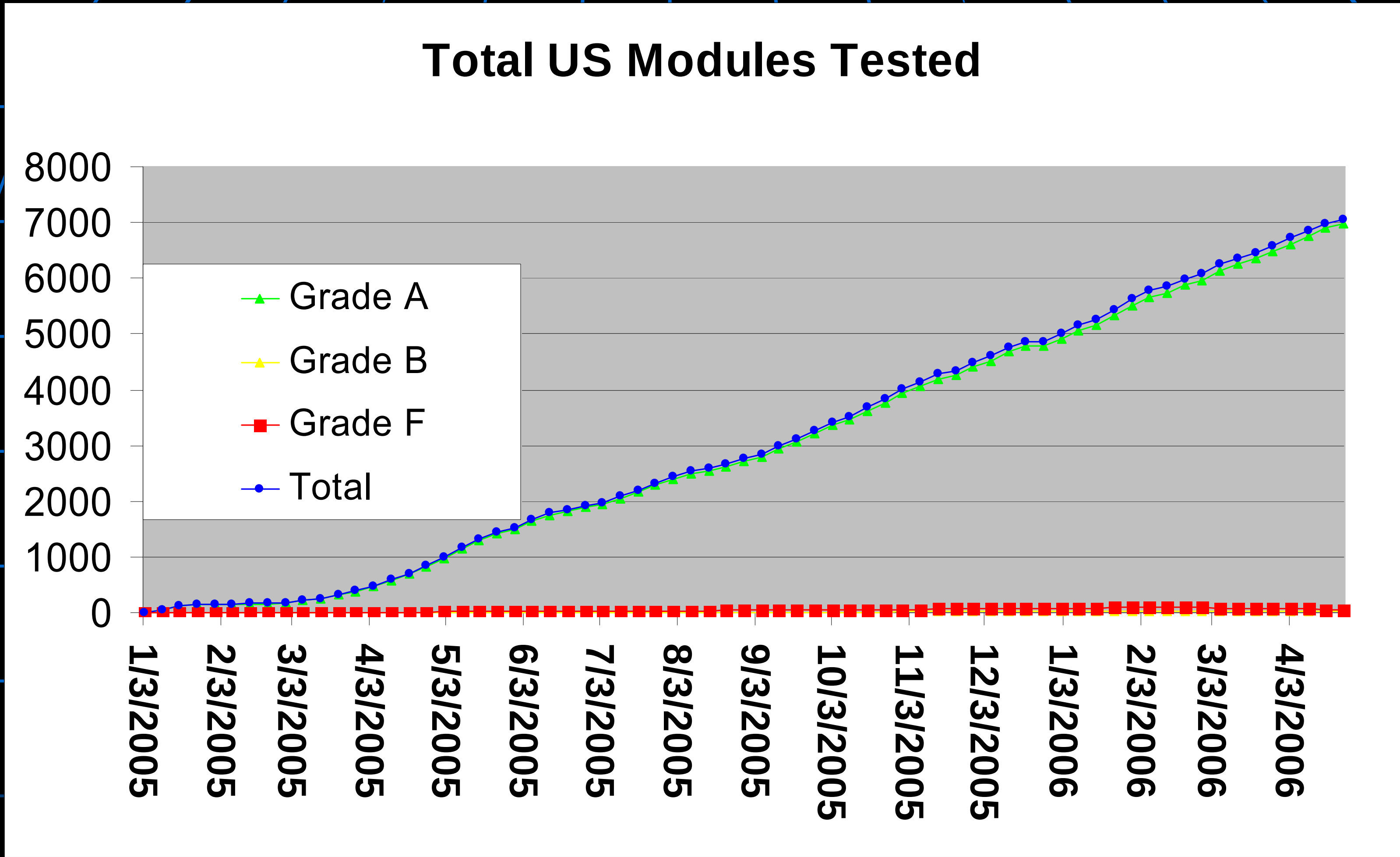
Sensor Corrosion

Discovered by Strasbourg and Karlsruhe then confirmed by STM



Micro-corrosions of the aluminum surface:

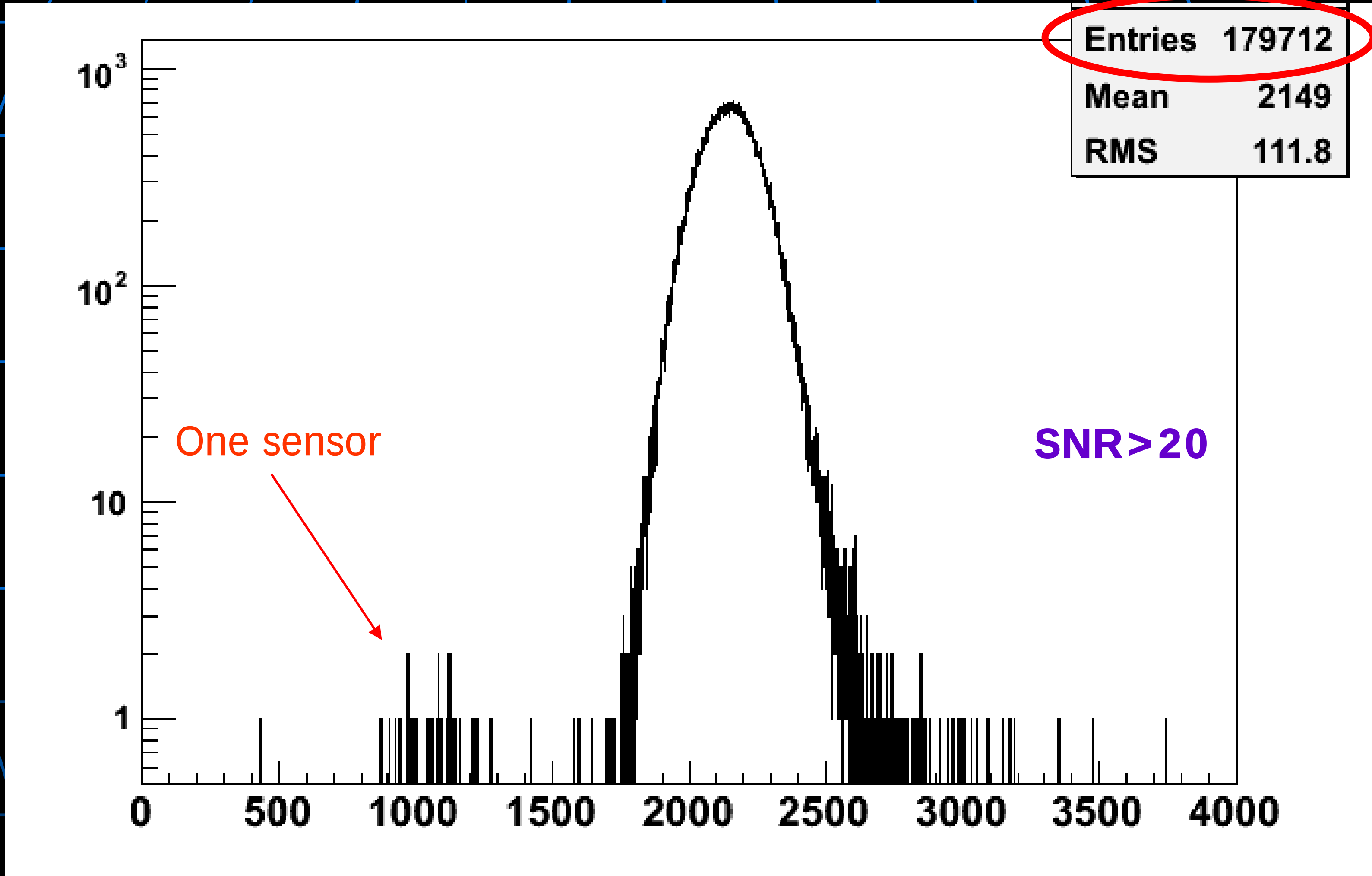
Humidity reacts with Phosphorus (present in a 4% concentration in the passivation oxide) and forms an acid (probably H_3PO_4), that corrodes the Aluminum.



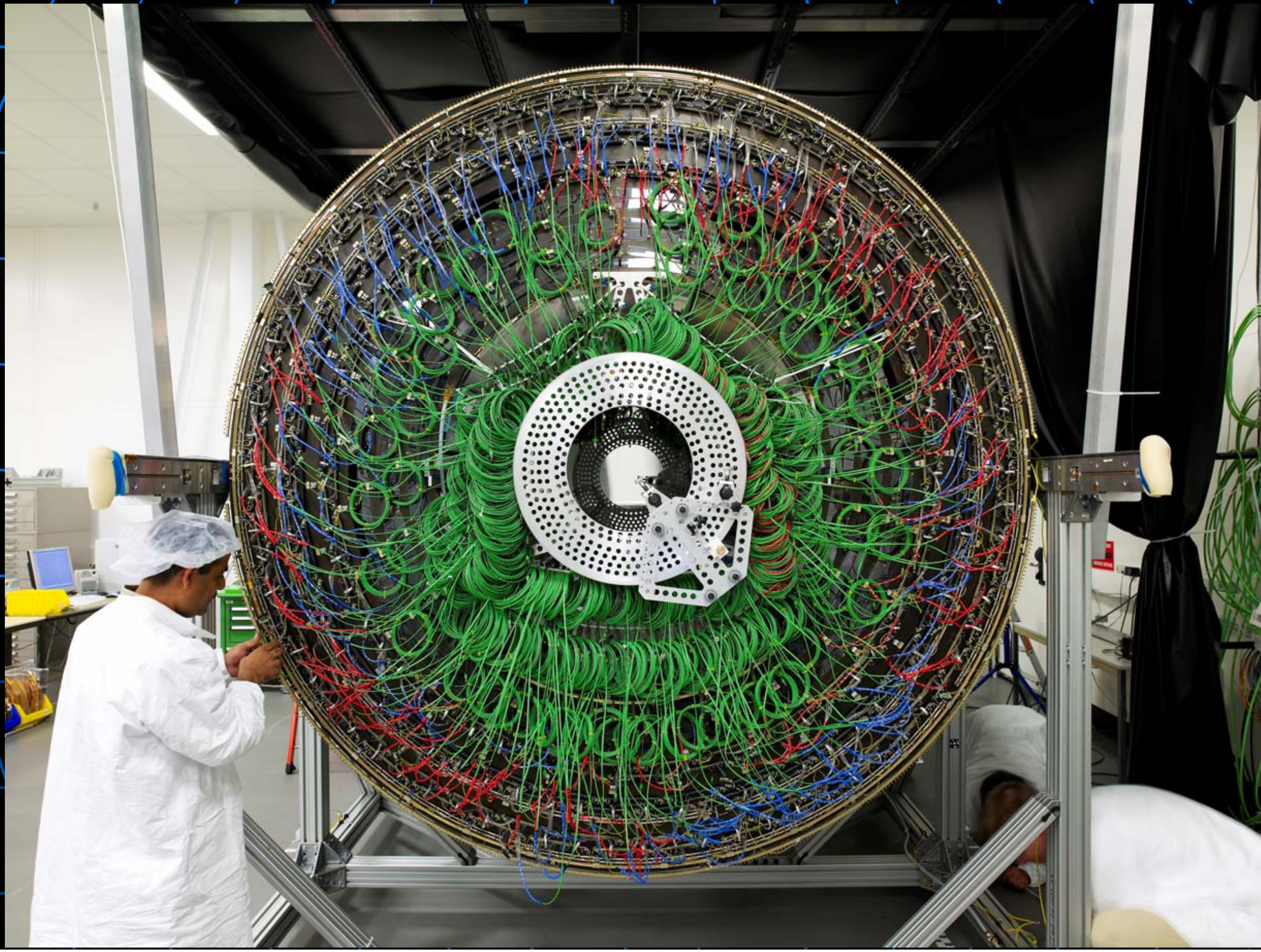
Built 7115 modules in ~1 year: 27 were not installable

2,644 bad channels out of 4,145,912

Noise after installation: 1 cooling segment



CMS: Tracker Outer Barrel



Conclusions (Lessons learned)

- R&D never really ends
  - Listen to the experts!
- No amount of preparation is too much
- Brinkmanship

  Somewhat like space-based detectors, once installed, there will not be access to many key elements.

  You have to get it right – this is more important than the schedule when it comes to making choices.

  Unfortunately this means *the project often lives on the critical path.*
- Don't forget your umbrella.

MODULE ASSEMBLY ON GANTRY