Silicon Detectors at DØ

Selected Aspects of Construction, Testing, and Performance

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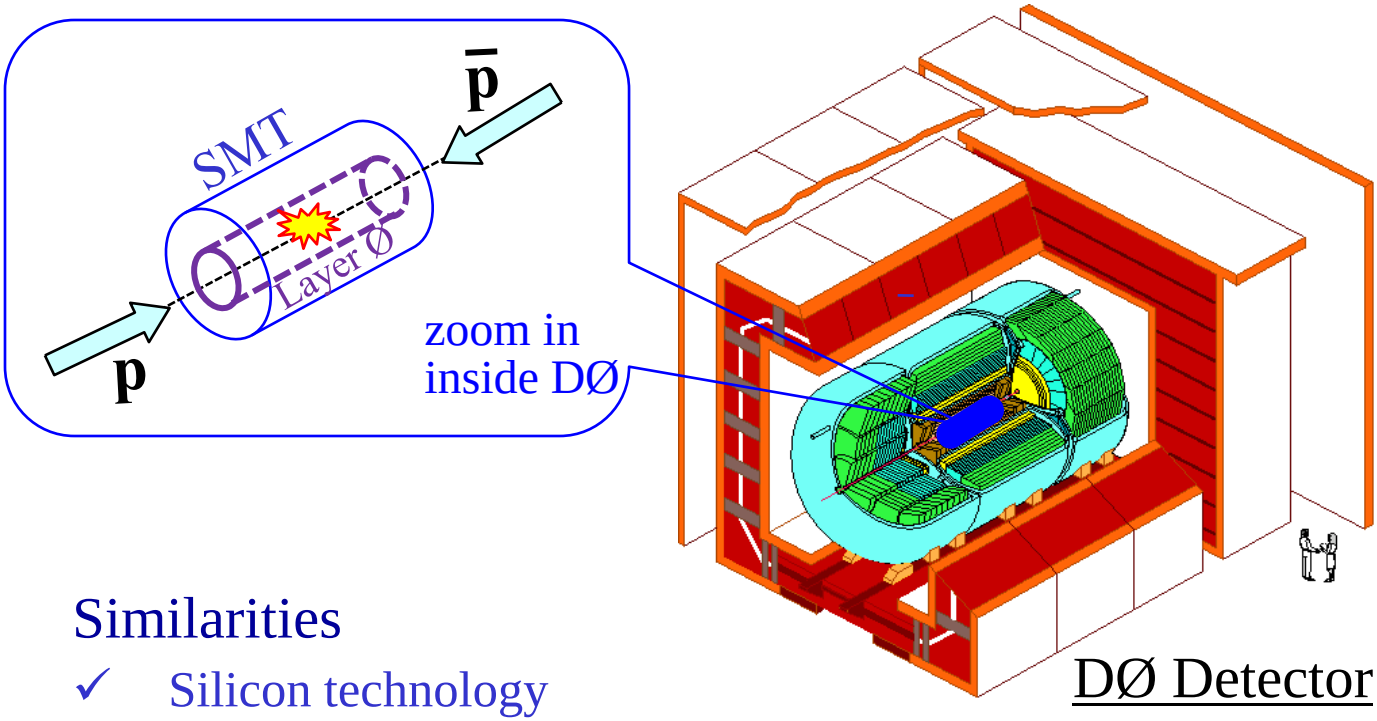
Introduction

- This presentation touches upon two sub-detectors of the DØ detector
  - ✓ Silicon Microstrip Tracker (SMT)
  - ✓ Layer Ø Detector



- Similarities
  - ✓ Silicon technology
  - ✓ Detect hits due to charged particles
    ⇒ reconstruction of tracks in a p-p̄ collision at DØ

- Time of operation
  - ✓ SMT : 2001 (RunII DØ upgrade) – today*
  - ✓ Layer Ø : 2006 (RunIIB DØ upgrade) – today*

* cosmic data

Outline

1. Silicon Microstrip Tracker (SMT)
2. Case for Upgrade
3. Layer Ø Detector

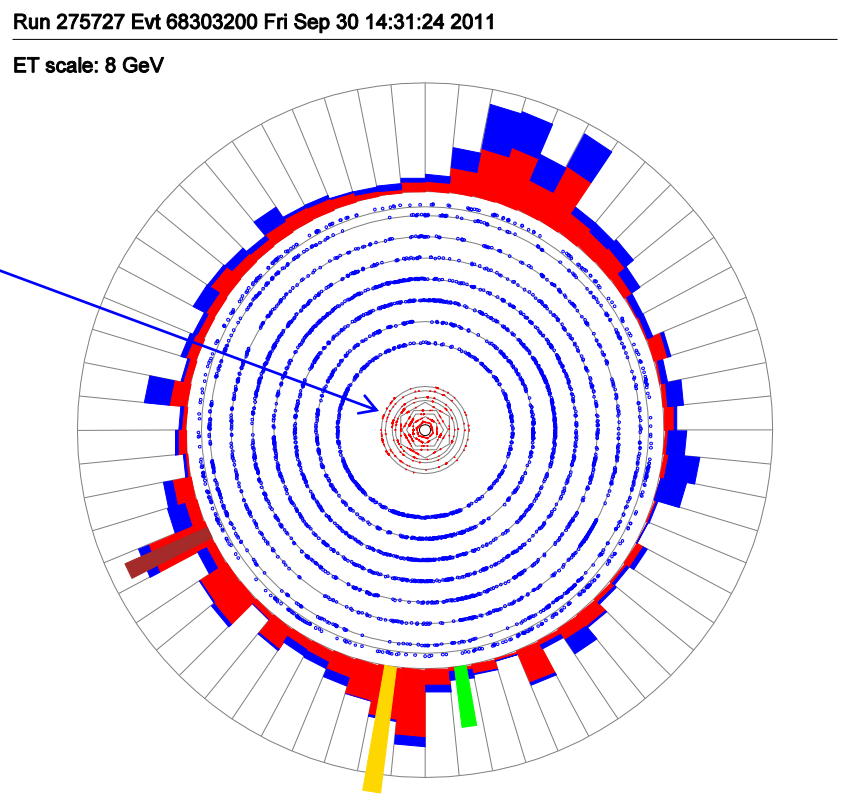
Outline

1. Silicon Microstrip Tracker (SMT)
   - Mechanical Design
   - Detector Assembly
   - Alignment
   - Positioning Tolerances
   - Production Quality Control Chain

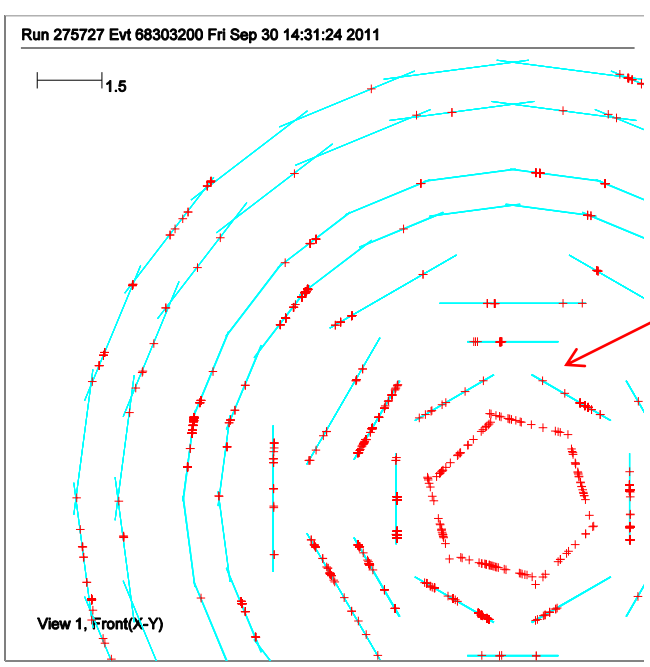
2. Case for Upgrade
   - Physics of Silicon Detector Operation
   - Radiation Damage Effects
   - Monitoring Radiation Damage

3. Layer Ø Detector
   - Software Upgrade
   - Monte Carlo Simulations
   - Tests at Assembly Site
   - Tests After the Installation in the Collision Hall

DØ Event from the Last Second of Tevatron Data



silicon detectors



hits in silicon detectors

Part 1

Silicon Microstrip Tracker (SMT)

SMT Design Considerations

1. SMT design goal: provide both tracking and vertexing over the full solid angle coverage of the calorimeter and muon systems

2. Tevatron machine parameters, e.g. bunch size

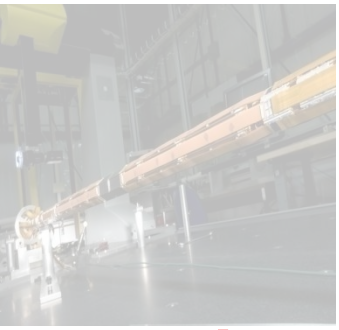
3. Various detector features necessary to achieve the designed tracking performance, e.g. precise alignment of detector elements and minimal mass

4. Meet simultaneously electrical, mechanical, and thermal requirements

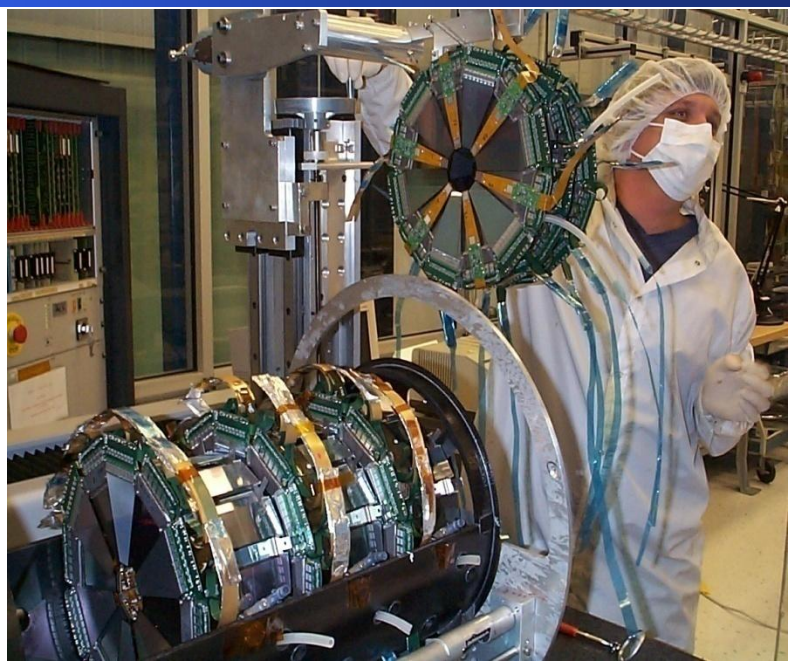
5. Fit inside the Central Fiber Tracker (CFT)

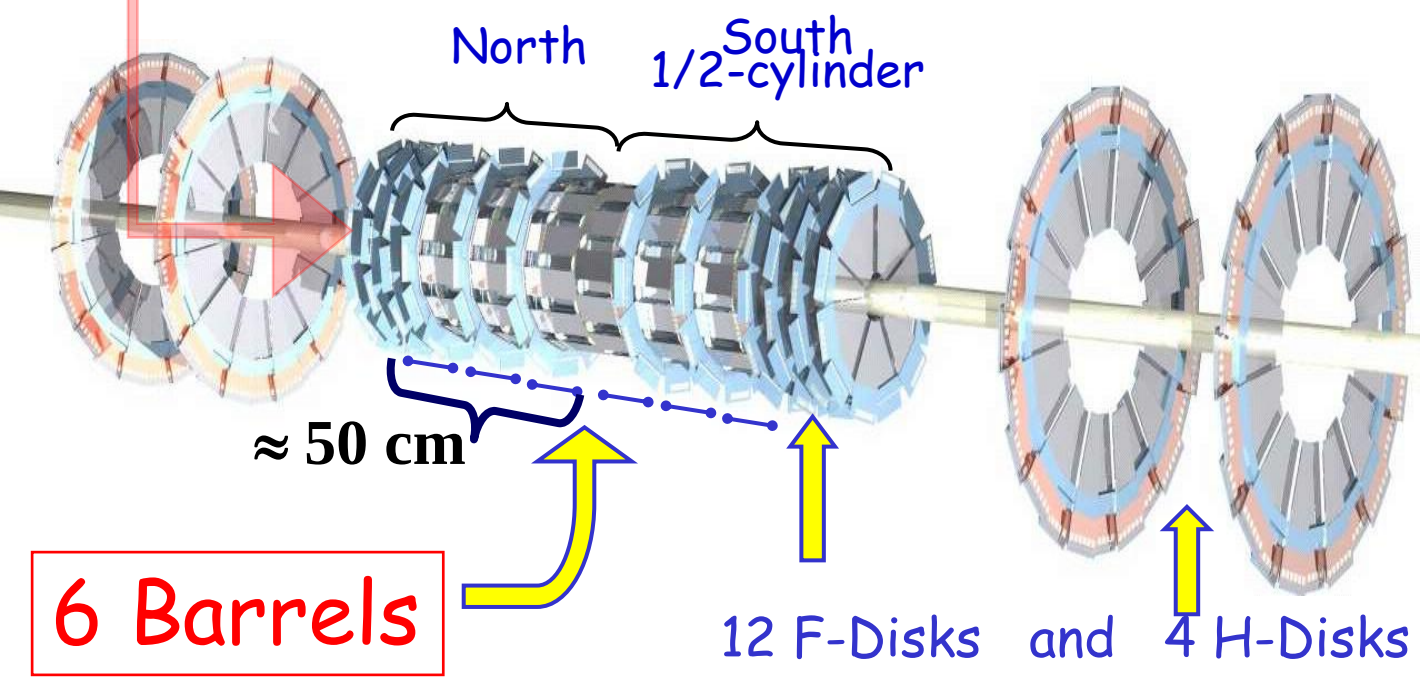
$\Rightarrow$ Barrel/Disk Design

Isometric View of the SMT



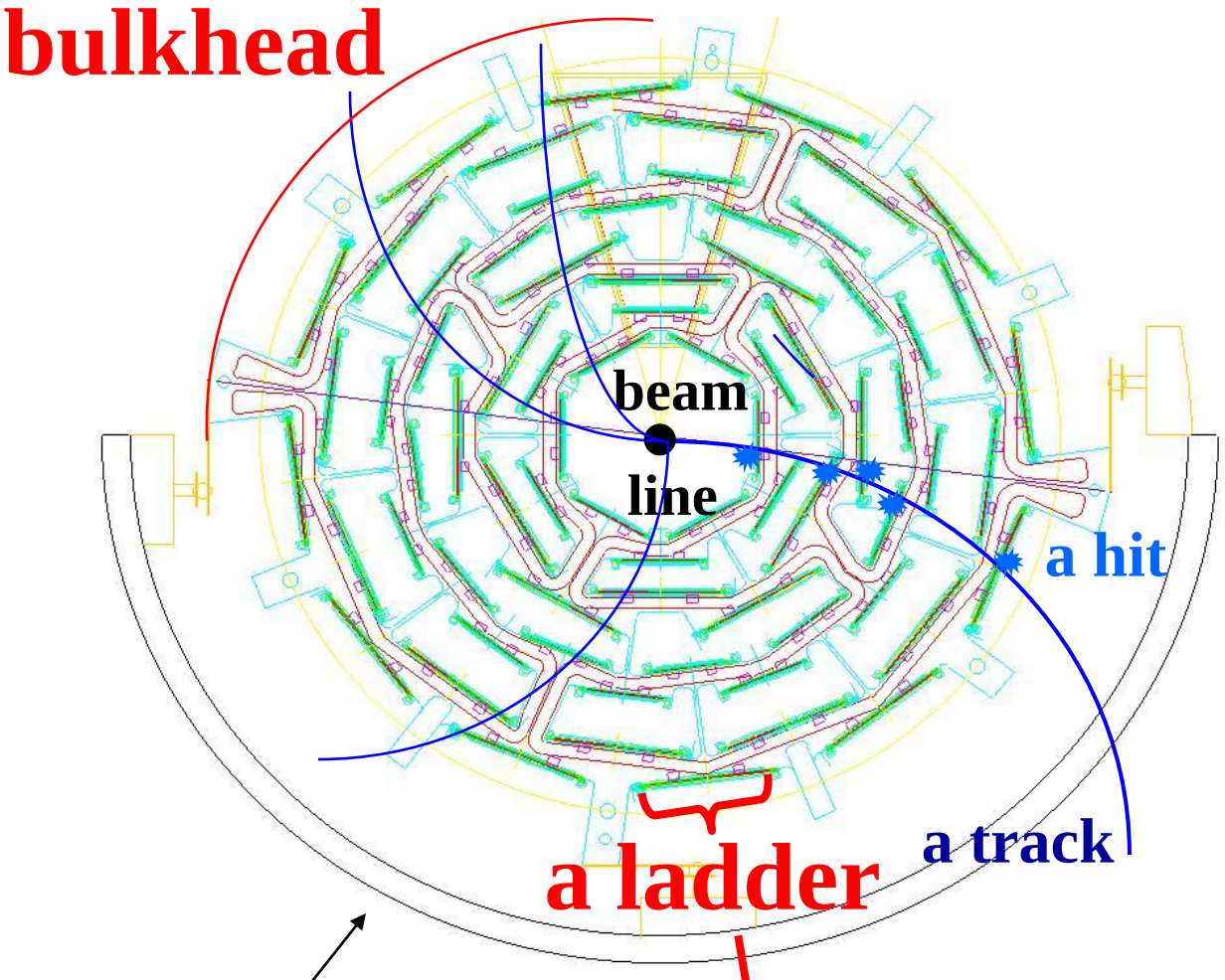
LØ detector was installed inside the SMT



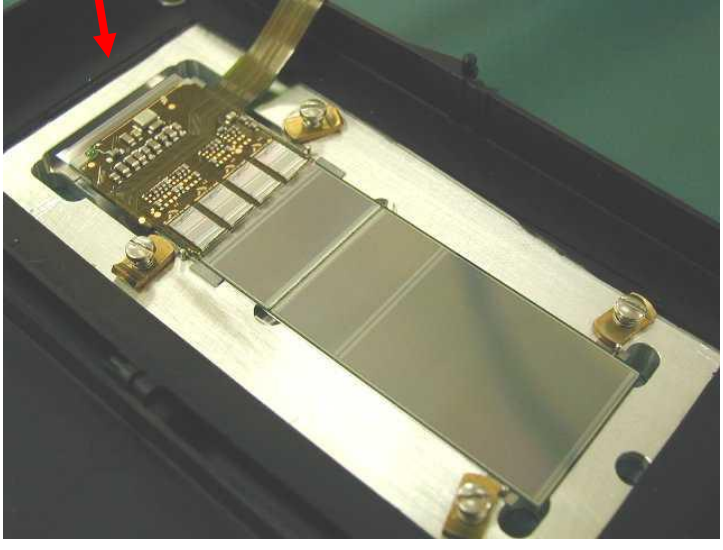


Barrel/Disk Design

Transverse View of a Barrel

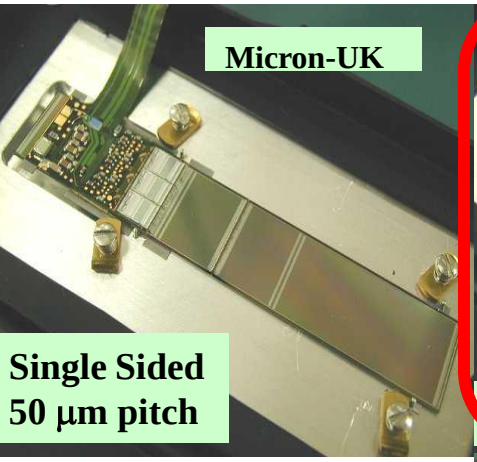


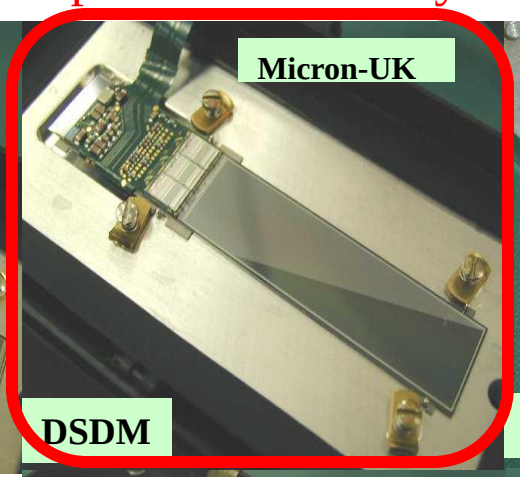
SMT outer
support structure

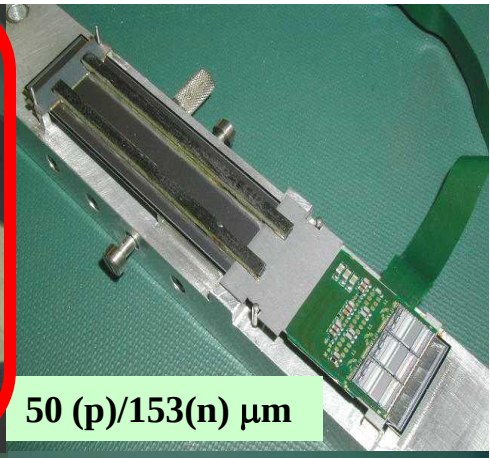


Unit Detector Elements

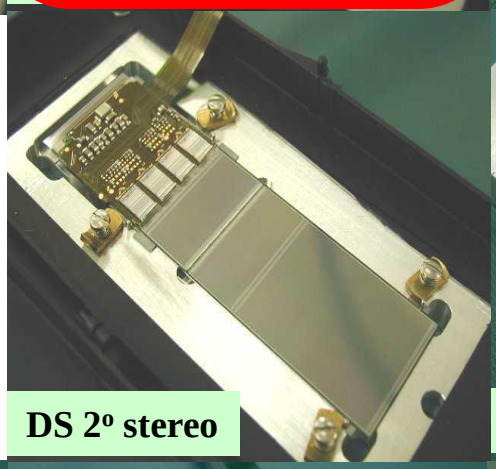
present here today

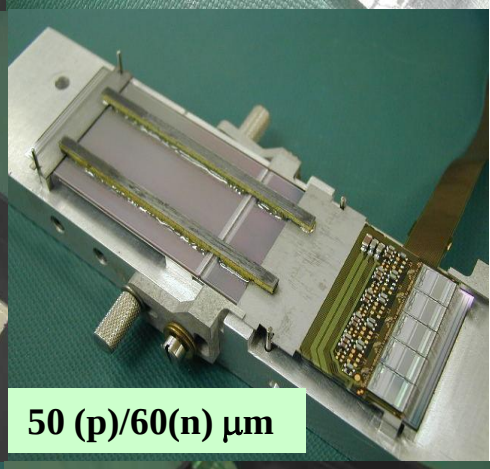


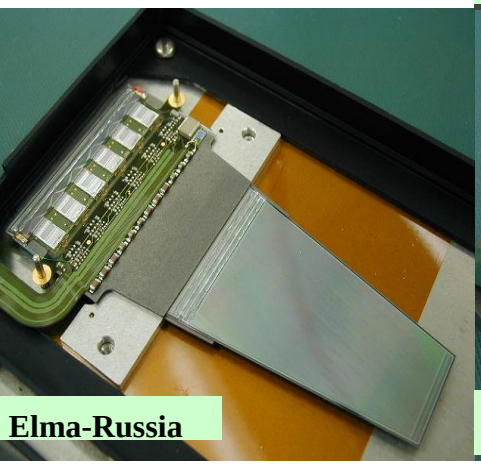


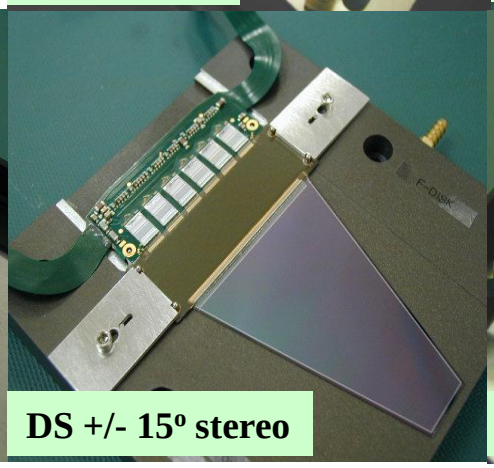


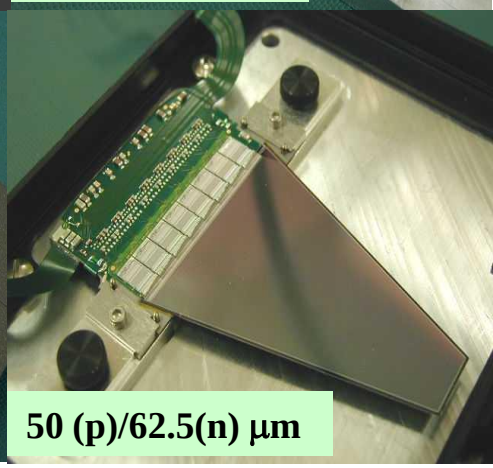
Family of DØ SMT Detector types



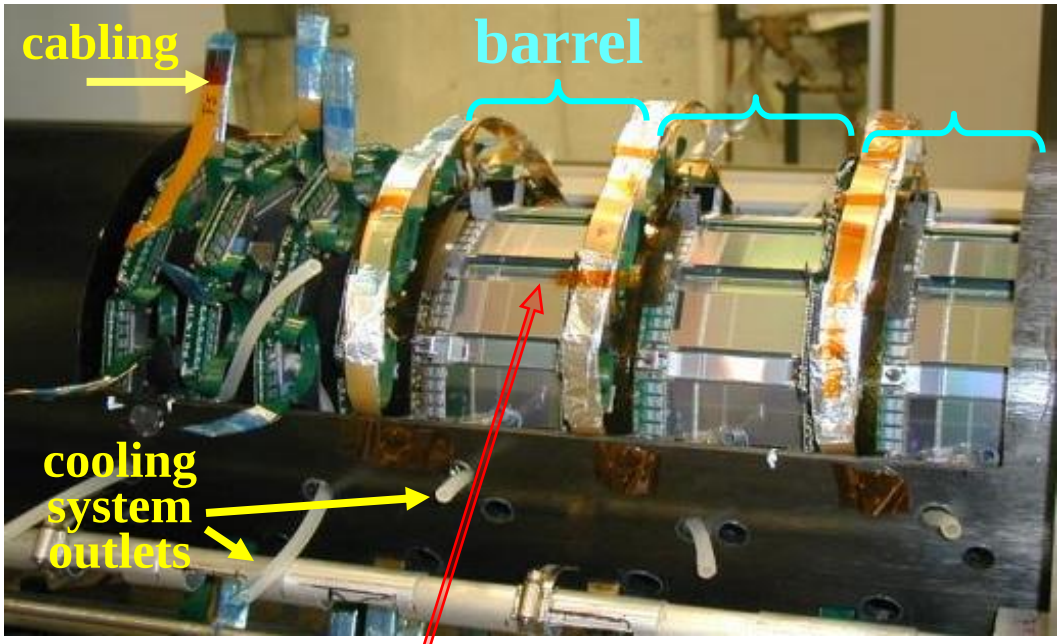




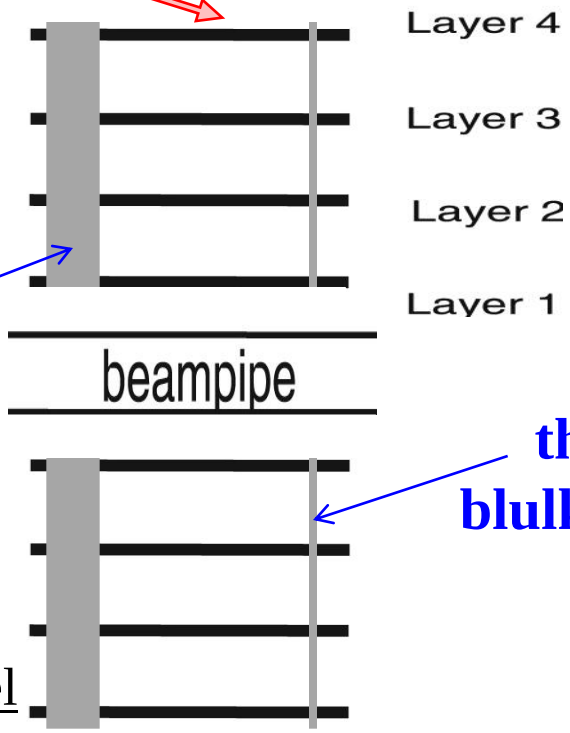




Longitudinal View



a ladder on the
outermost layer

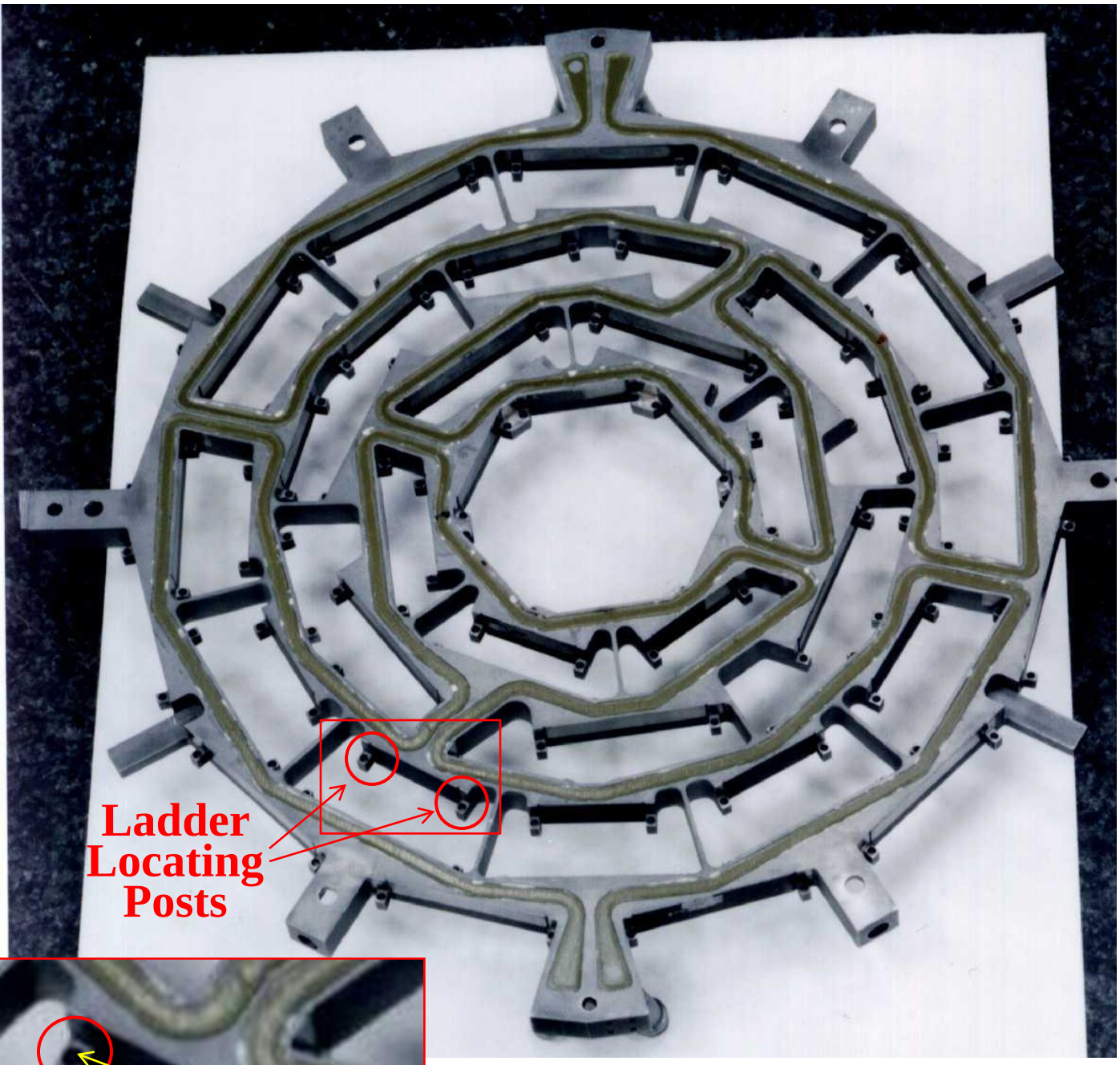


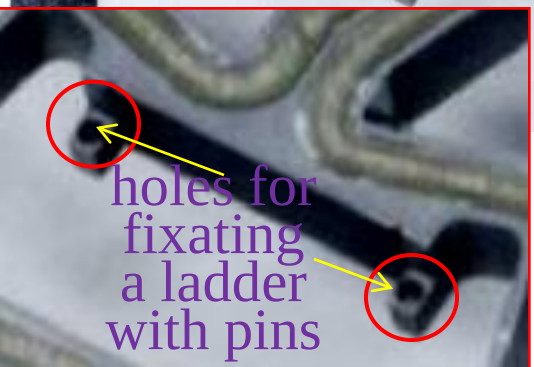
cooled
blulkhead

thin
blulkhead

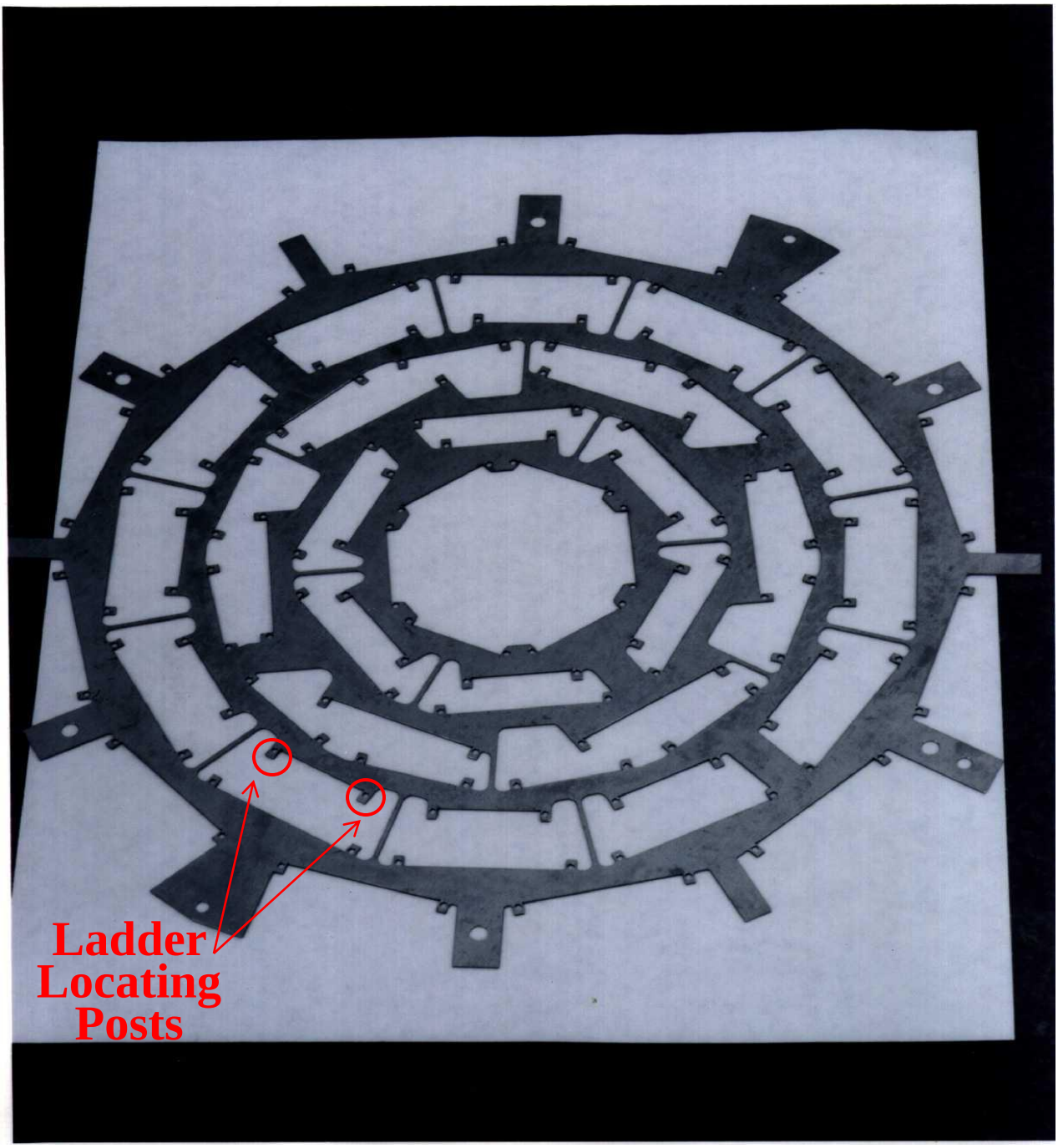
cross-sectional
cartoon of a barrel

Cooled (Active) Bulkhead

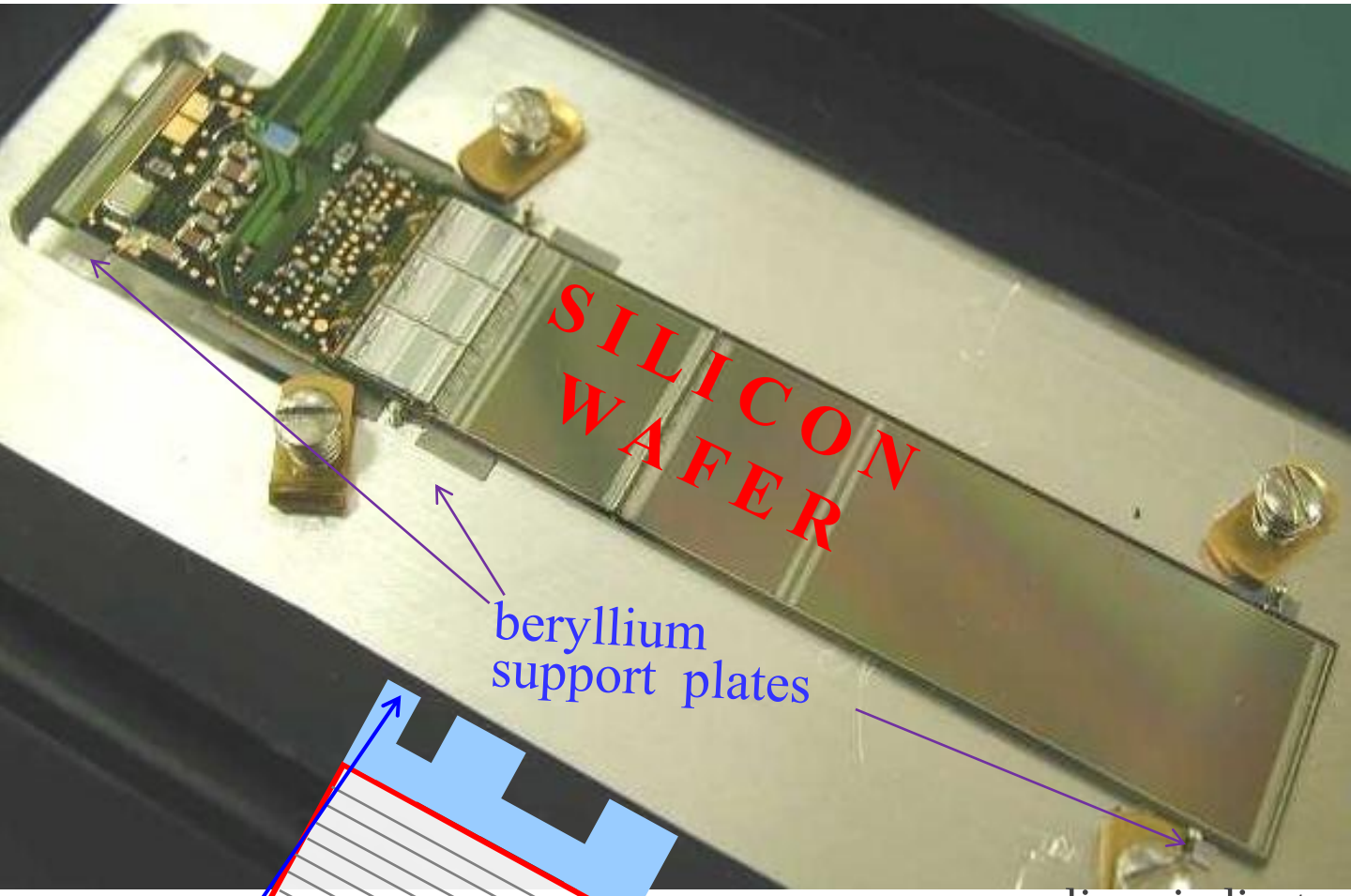


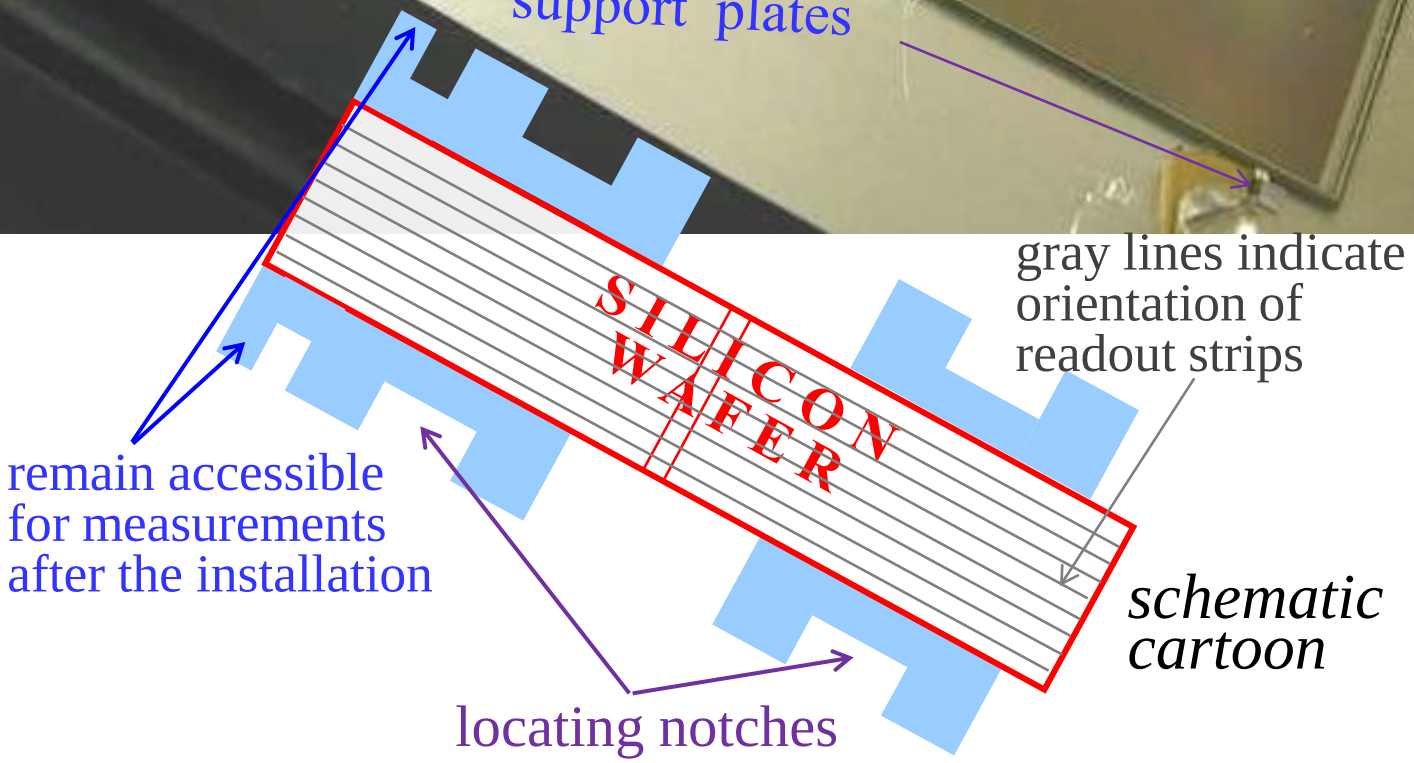


Thin Bulkhead

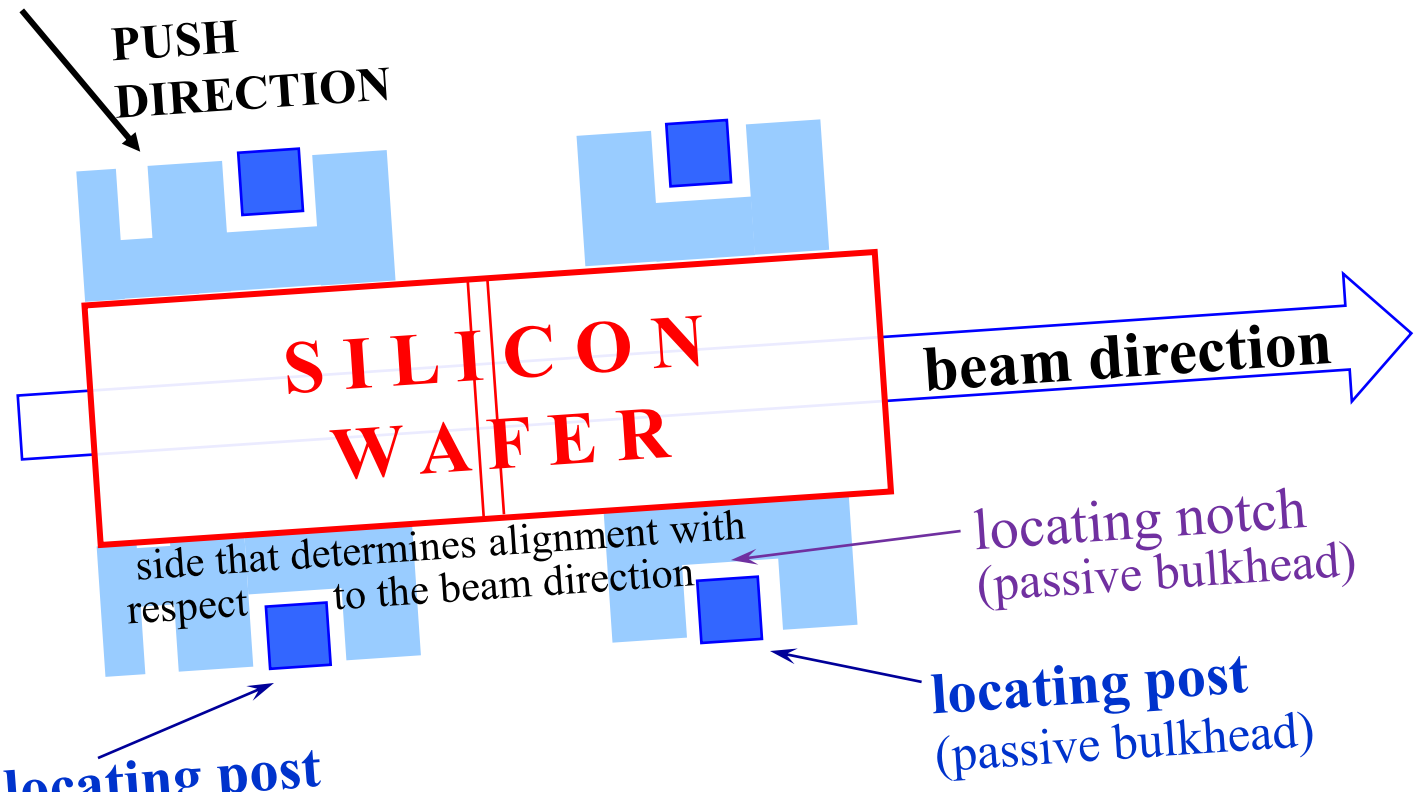


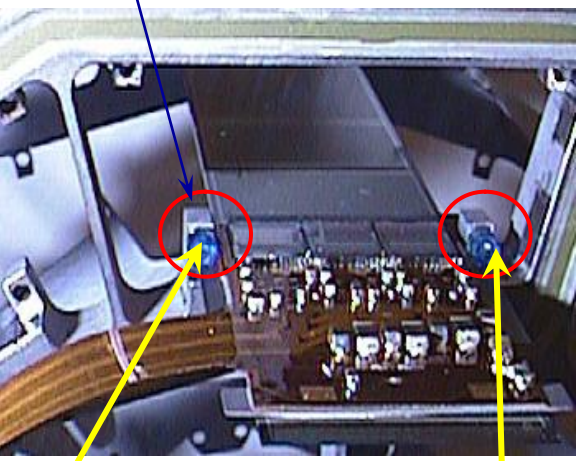
Close up on a Ladder



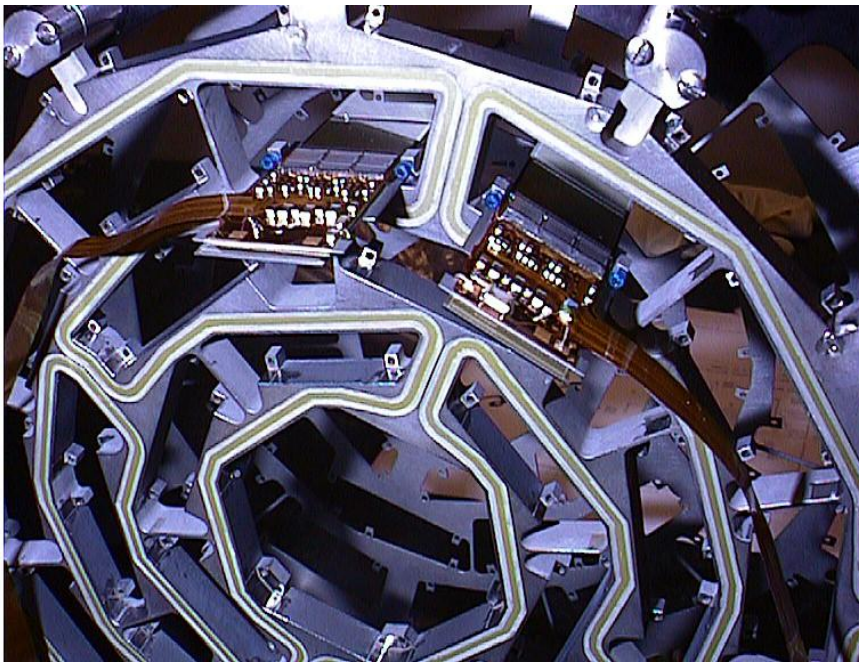


Mounting Ladders on Bulkheads





fixating pins inserted into the openings in the bulkhead post



Alignment

Let us discuss three aspects of ladder alignment:

How do we

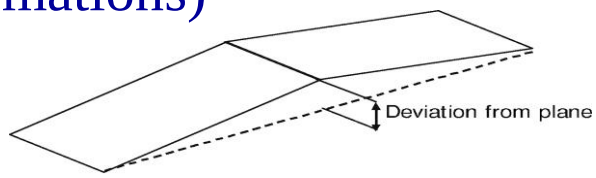
1. determine the position of active material *(location of readout strips on the silicon sensor in the global coordinate system)* after the ladder installation *?*

2. define positioning tolerances ?

3. ensure the tolerances are met ?

Correctable Shifts

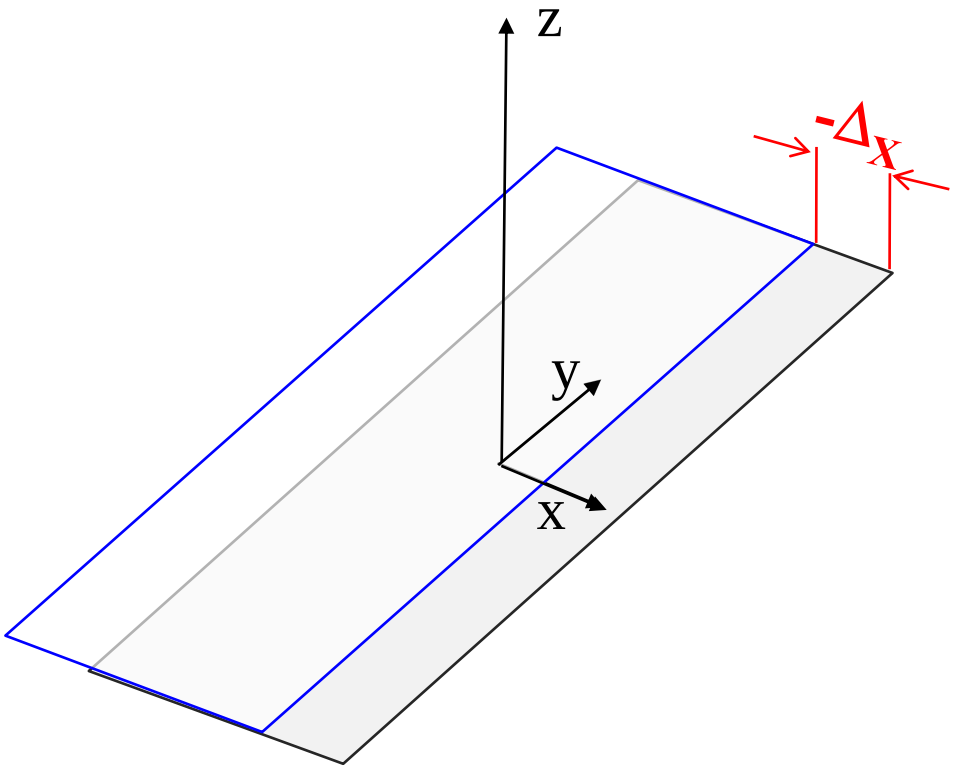
- (assuming no internal deformations)
  ⇒ six degrees of freedom



- Displacement from the nominal global position can be described by three shifts and three rotations

- In principle, a known displacement can be corrected in the offline track reconstruction software

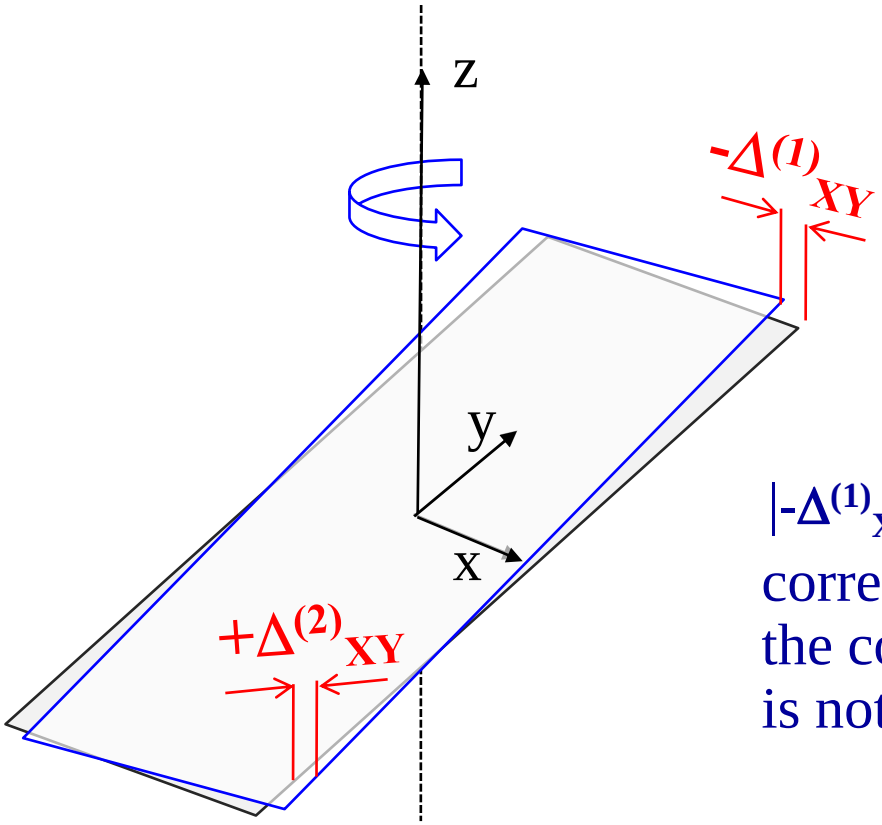
Example: constant shift along the width of the ladder*



* readout strips run along the length of the ladder

Uncorrectable Rotations

in case of single-sided ladders (1D axial hit info only) this rotation cannot be corrected for



$|-\Delta^{(1)}_{XY}| \neq |+\Delta^{(2)}_{XY}|$

correction depends on the coordinate which is not known (y)

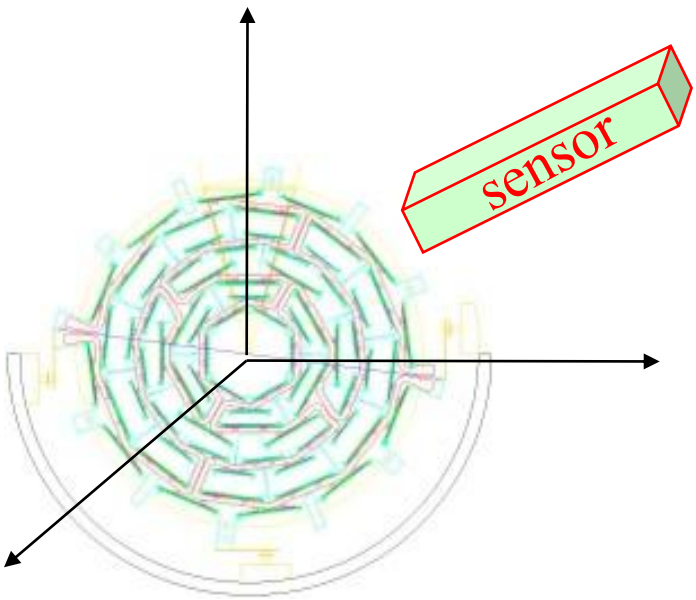
tolerance was determined from the SMT simulation:

$|\Delta_{XY}| < 25\ \mu m$

with analysis of track impact parameter resolution

Determining Global Position of Silicon Sensor

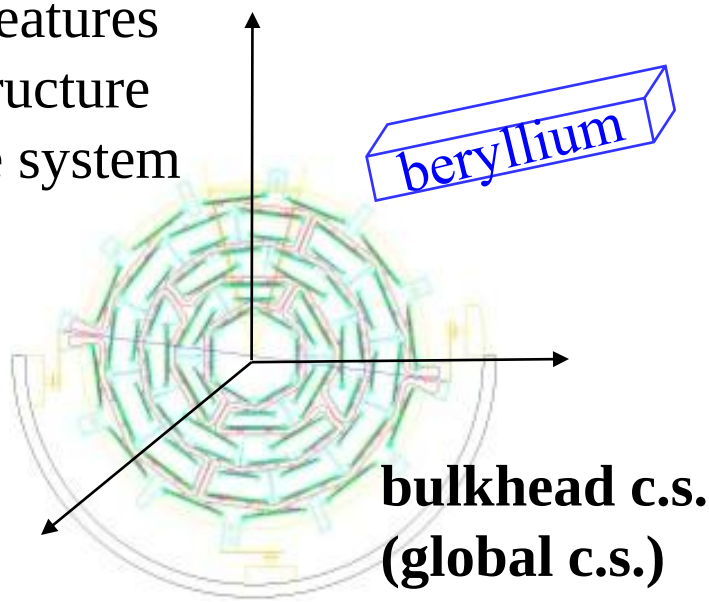
global position of a sensor = ?



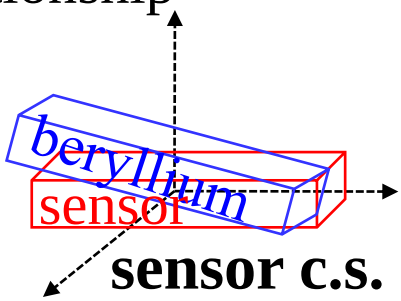
bulkhead coordinate system
(global coordinate system)

Determining Global Position of Silicon Sensor (Cont'd)

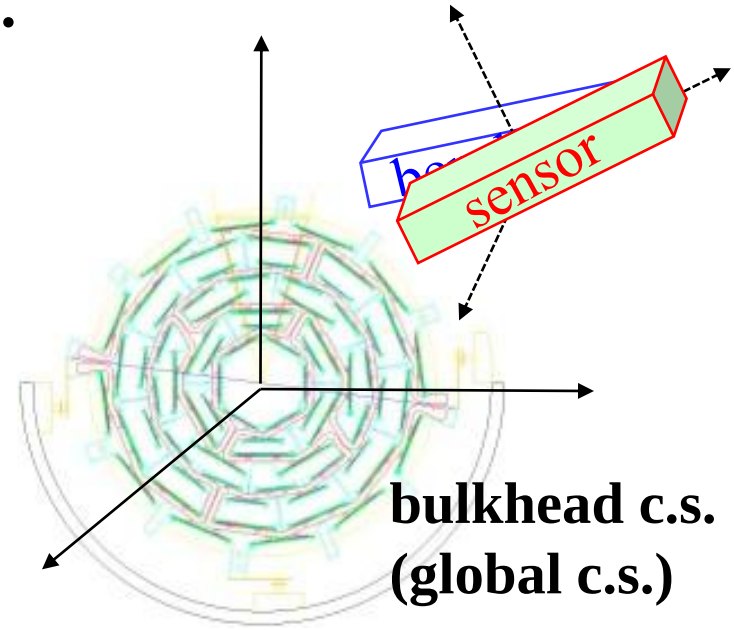
1. Measure accessible features of beryllium support structure in the global coordinate system



2. beryllium ↔ silicon relationship

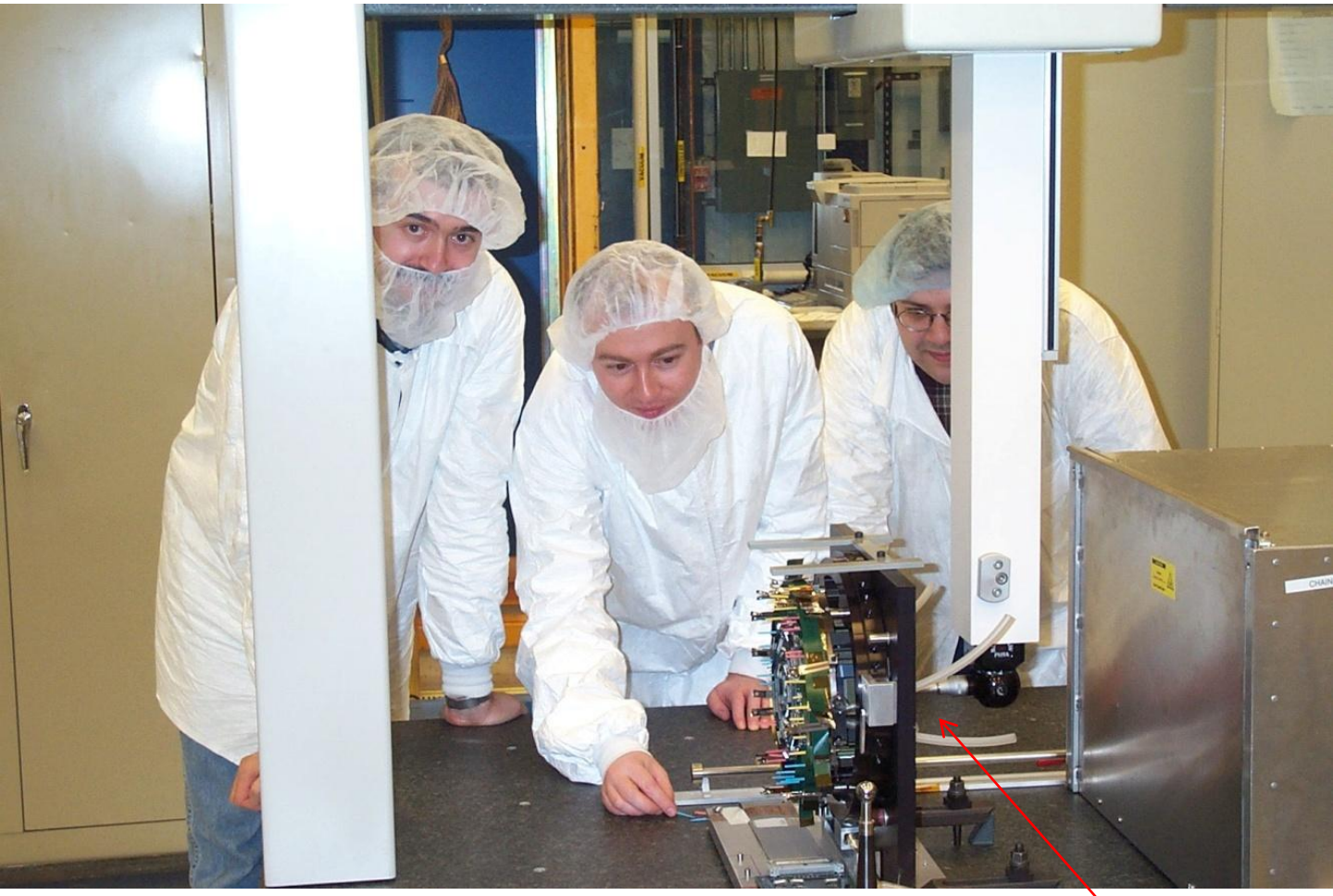


3. Combine 1) and 2)



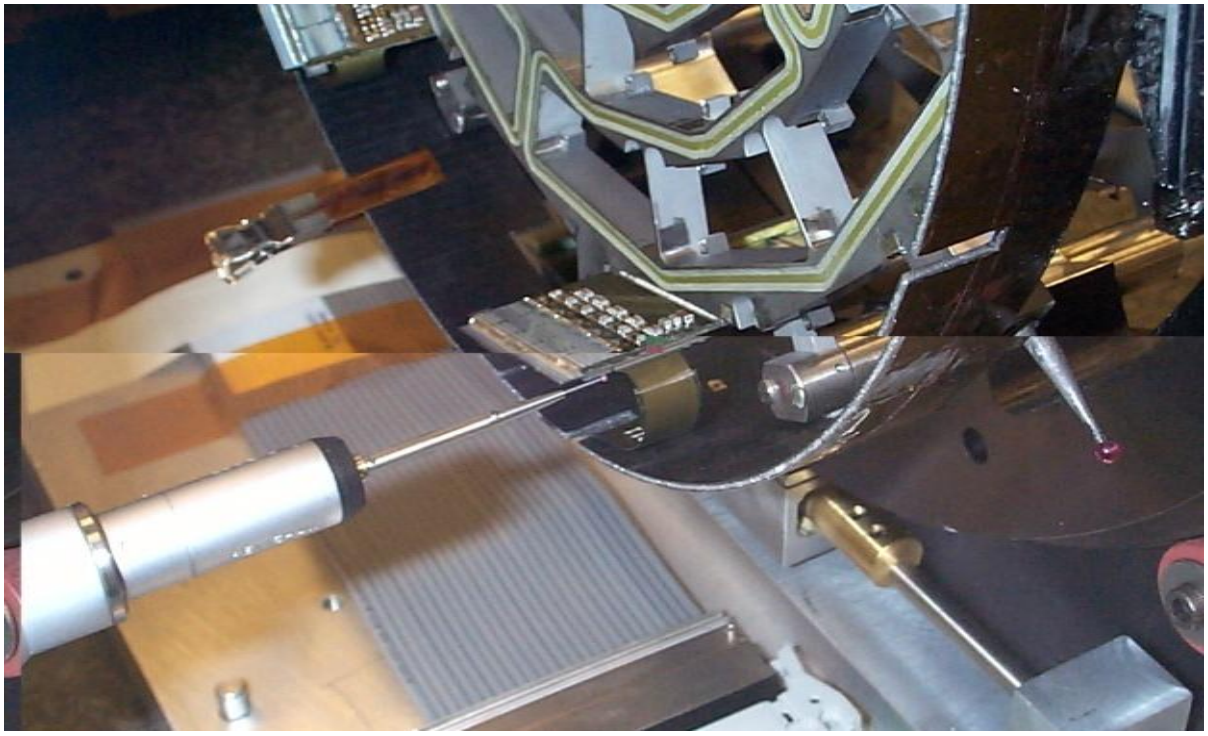
Measuring Accessible Features with Touch-Probe Machine

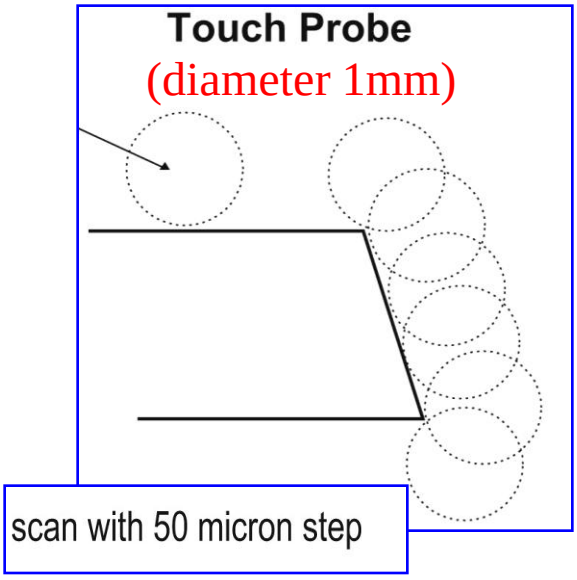
assembly crew runs touch-probe survey program immediately after ladder installation

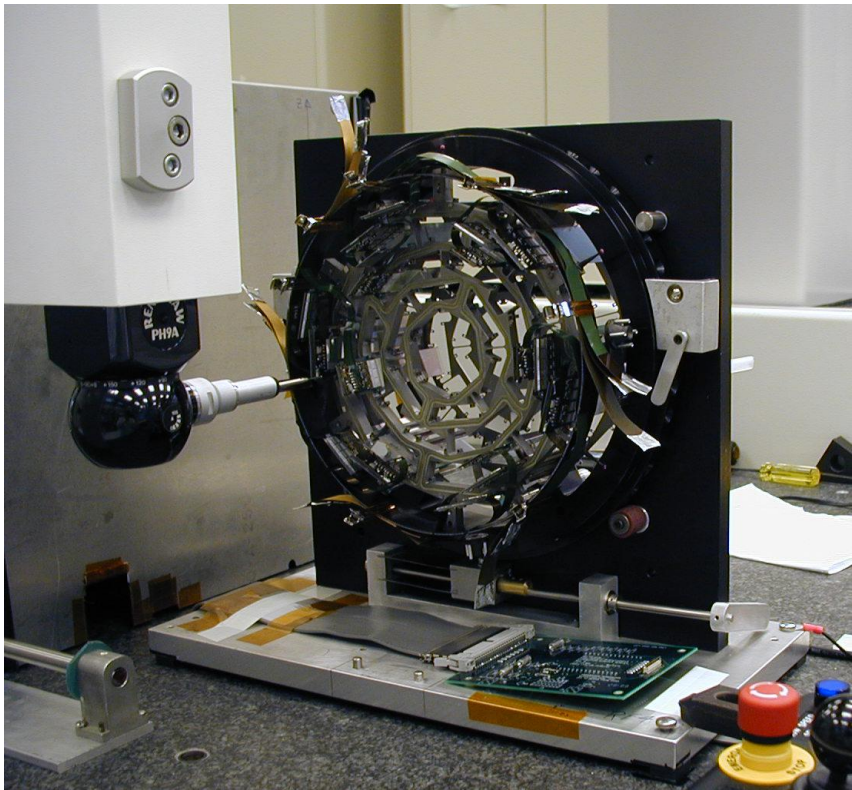


touch-probe surveys ladders on the passive bulkhead side

Touch Probe Survey

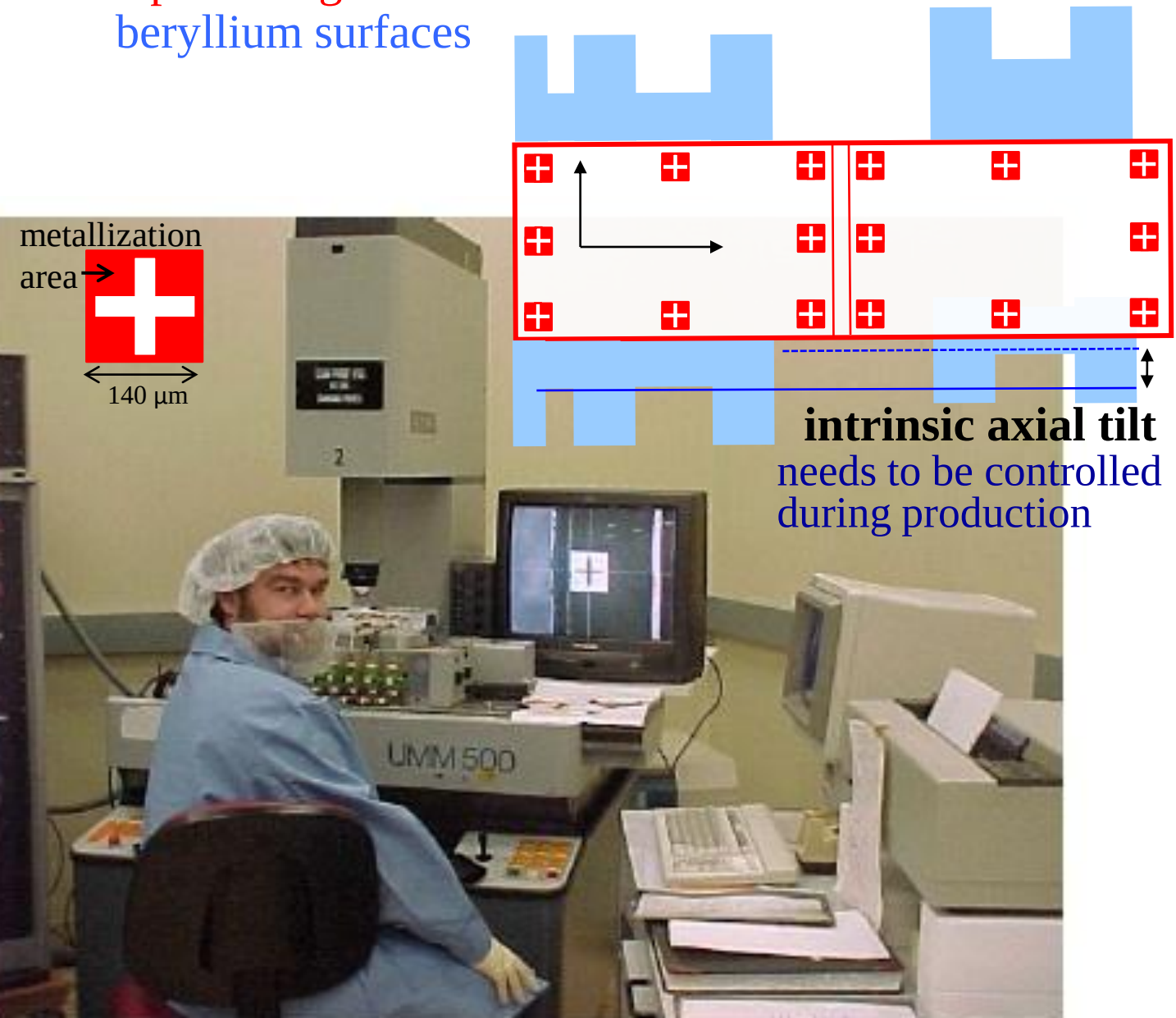






Optical Measurements

- Silicon sensor position is inferred from touch-probe survey data, using pre-installation measurements of the ladder
- Optical targets on silicon sensors were linked to beryllium surfaces



intrinsic axial tilt
needs to be controlled during production

Setting Up Quality Control Chain

- Write a program which
  - ✓ performs complete analysis of the measurement data
  - ✓ informs a user whether the ladder meets assembly tolerances or not
  - ✓ stores summary information in the database

- Set up quality control chain
  - ✓ dedicated computer in the clean room
  - ✓ instructions for a technician to run the program

Using Data-Processing Program

- choose ladder type
- choose to process one(many) ladder(s)
- press START button
- check for misalignments beyond tolerance
  (will appear in red on the bottom right of the screen)
- press EXIT button

Y NOMINALS , mm NOMINALS		X MEASURED , mm VALUES	Y	X RESIDUALS	Y , microns
0.000	Active CL	-0.00117	0.00041	-1.2	0.4
0.000	Active CR	59.75763	0.00020	-1.4	0.2
-10.480	Active BL	-0.00110	-10.47979	-1.1	0.2
-10.480	Active BM	29.88050	-10.48019	0.5	-0.2
-10.480	Active BR	59.75810	-10.48000	-0.9	0.0
10.480	Passive TL	60.12455	10.48000	0.6	0.0
10.480	Passive TM	90.00295	10.47979	-1.0	-0.2
10.480	Passive TR	119.88435	10.47999	1.4	0.0
0.000	Passive CL	60.12482	-0.00020	0.8	-0.2
0.000	Passive CR	119.88483	0.00019	1.8	0.2
-10.480	Passive BL	60.12570	-10.48060	1.7	-0.6
-10.480	Passive BM	90.00450	-10.48041	0.5	-0.4
-10.480	Passive BR	119.88510	-10.48021	2.1	-0.2

Run Optionss

- [ ] 9chip
- [x] 3chip
- [x] Single File
- [ ] Folder

C:\SiDet\Lap
3*.txt

Start

Exit

		X1	X2	X Residuals	Y Residuals
TopActive X	X	37.40695	37.40595	27.8	
TopPassive X	X	113.09495	113.09215	-1.7	
BottomActive X	X	37.39510	37.39450	16.0	
BottomPassive X	X	113.08330	113.08350	-13.1	
11.0973	Y	11.10386	11.10446		7.2
11.0973	Y	11.10495	11.10395		7.7
-11.0973	Y	-11.09193	-11.09352		3.8
-11.0973	Y	-11.09185	-11.09105		5.5

Quality Control Chain

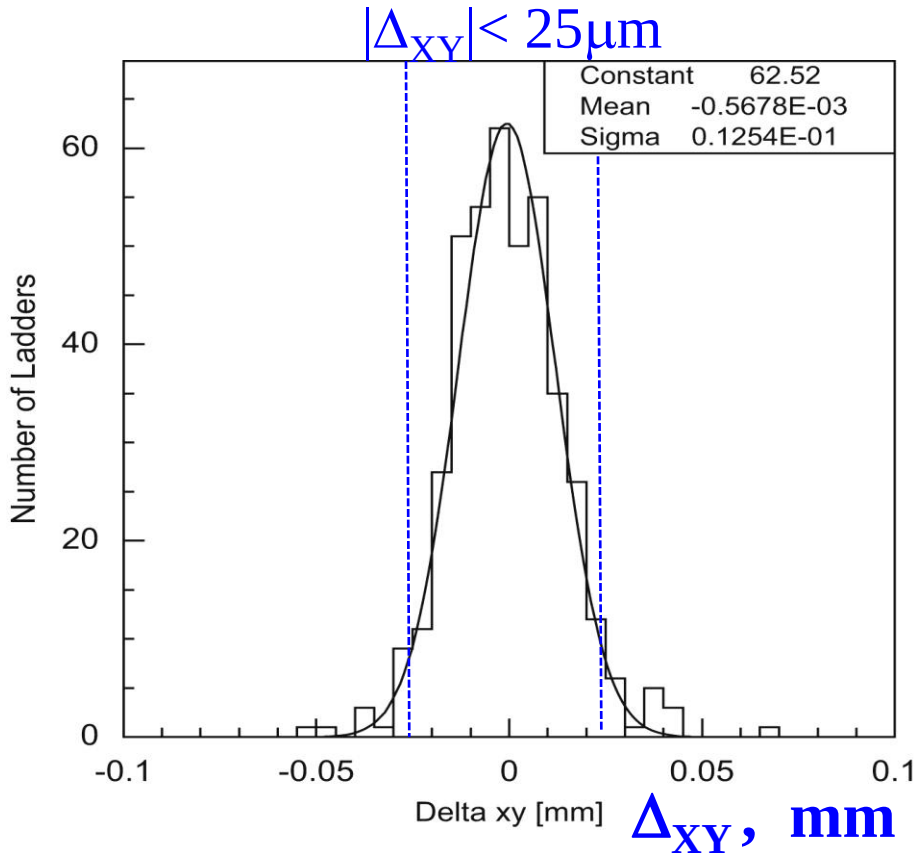
Technician

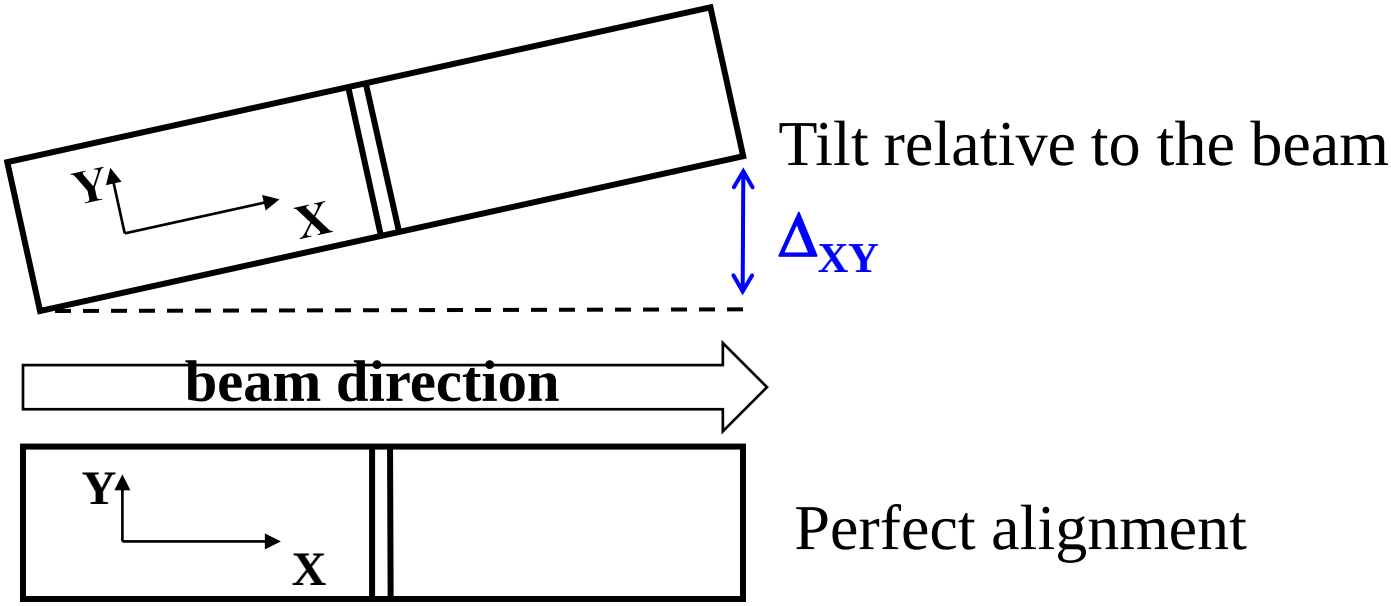
1. Perform optical measurements in the clean room at SiDet facility
2. Convert measurement data file from Coordinate Measuring Machine OS format into ASCII
3. Run Visual Basic Program to evaluate the quality of a ladder
4. "Database entry" is created automatically and sent out of SiDet facility over the network for analysis

Physicist

5. Analysis of the data processed with VB program
6. Decision if the ladder is suitable for installation

Touch Probe Survey Results
(after installation)





Part 2

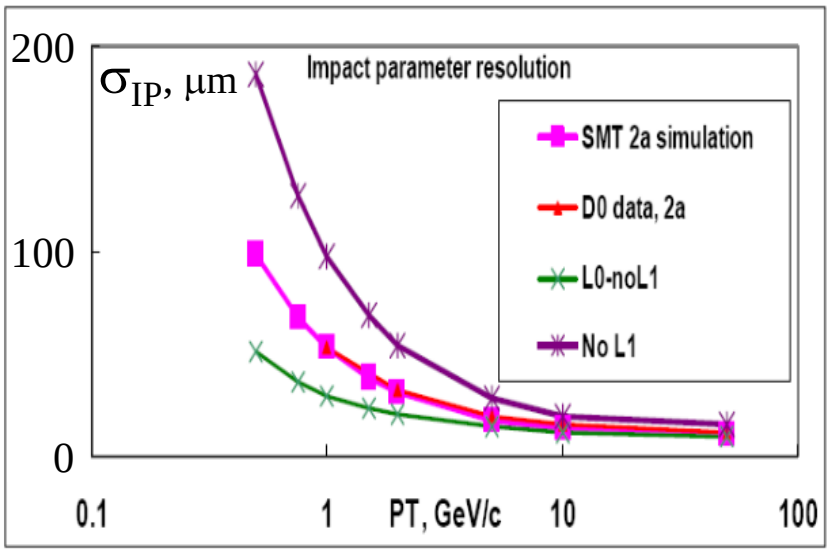
Case for Upgrade.
Radiation Damage

Why Layer Ø ?

- DØ Silicon Microstrip Tracker (SMT) was built to withstand 2 to 4 fb^{-1} of integrated luminosity originally projected for Run II

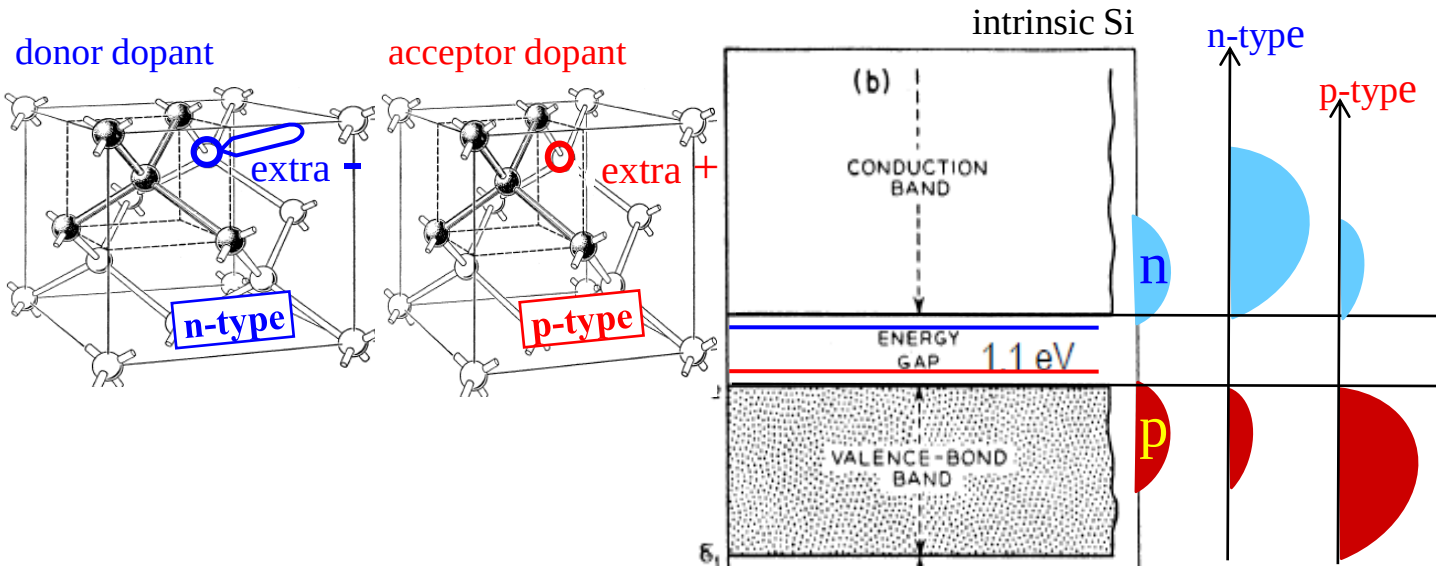
- 2004 Run II design goals opened the possibility that a total integrated luminosity of 8 fb^{-1} would be delivered to Tevatron Collider experiments

- In order to retain physics capabilities of the currently installed SMT and improve the impact parameter resolution, the addition of a single layer silicon detector (LØ) was proposed

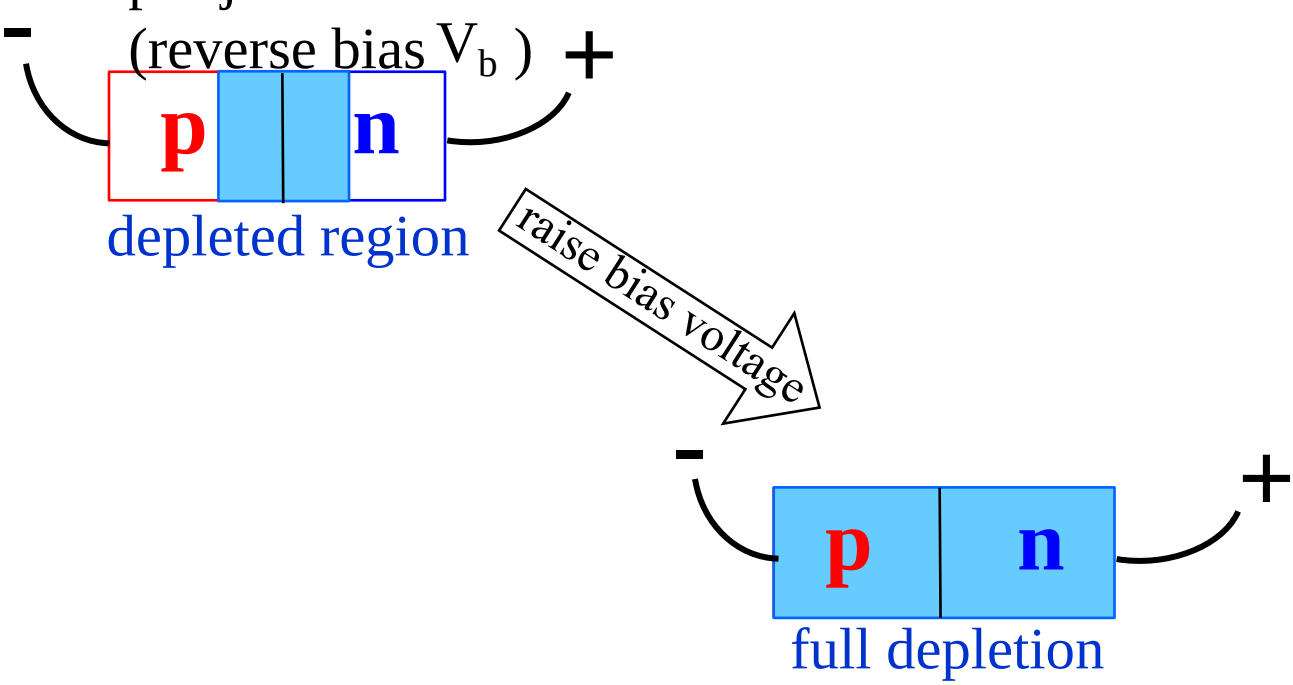


- LØ was installed and commissioned in spring – summer of 2006

p-n Junction

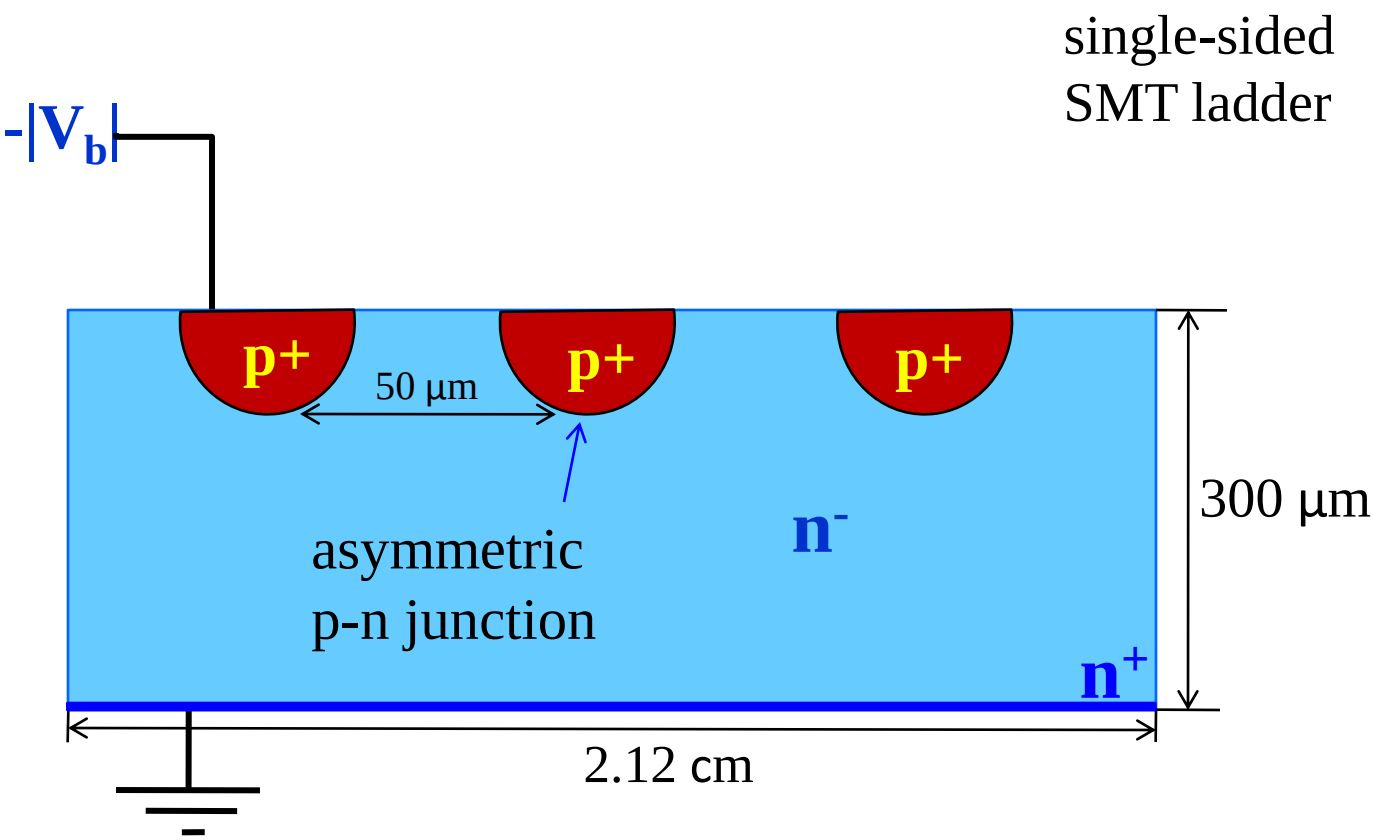


p-n junction
(reverse bias V_b)

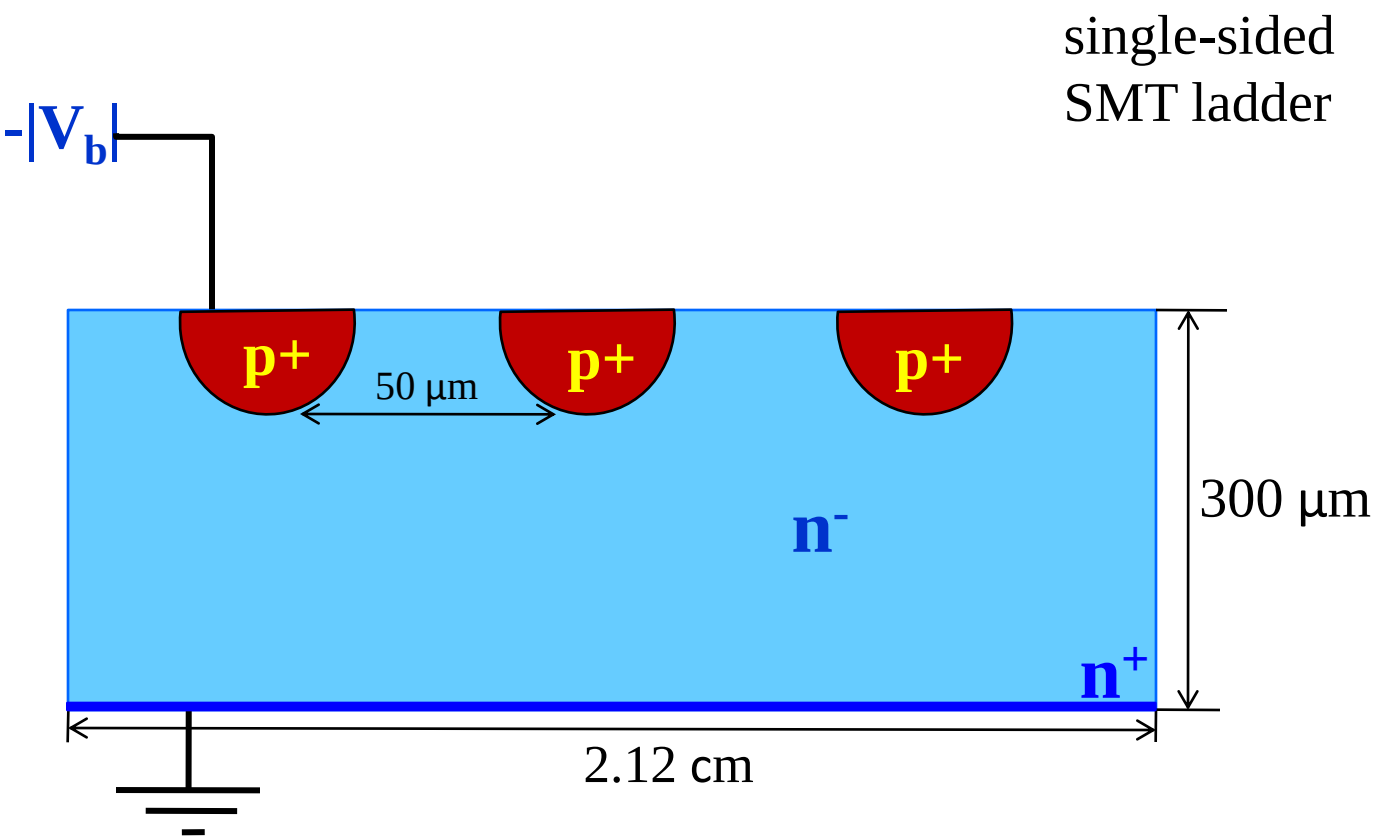


- dopant ion space charge
- no mobile carriers

Silicon Detector Operation



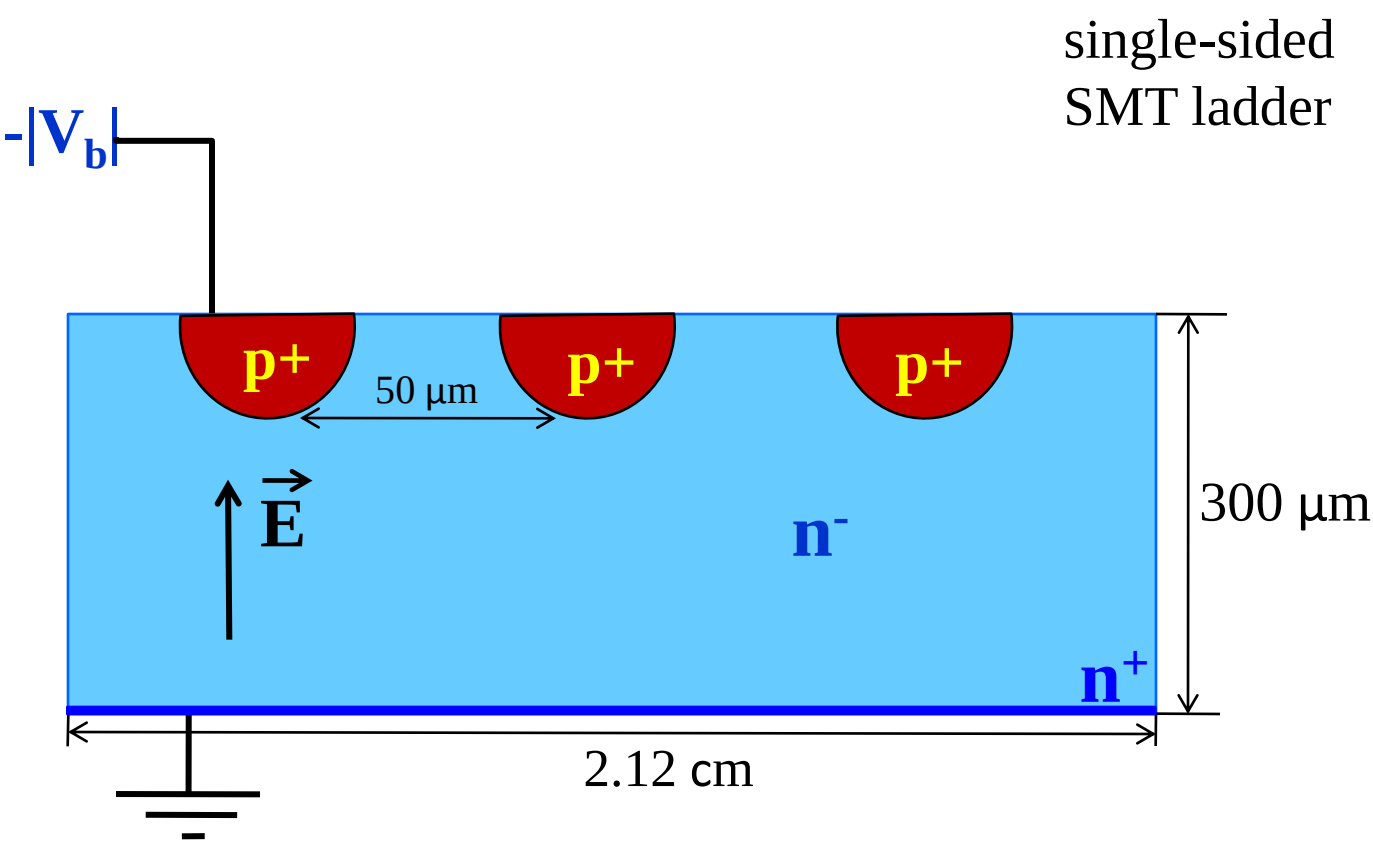
How Detector Works



$$\frac{d^2V}{dx^2} + \frac{Nq_e}{\varepsilon} = 0$$

- space charge in the bulk
- boundary conditions

How Detector Works



$$\frac{d^2V}{dx^2} + \frac{Nq_e}{\varepsilon} = 0$$

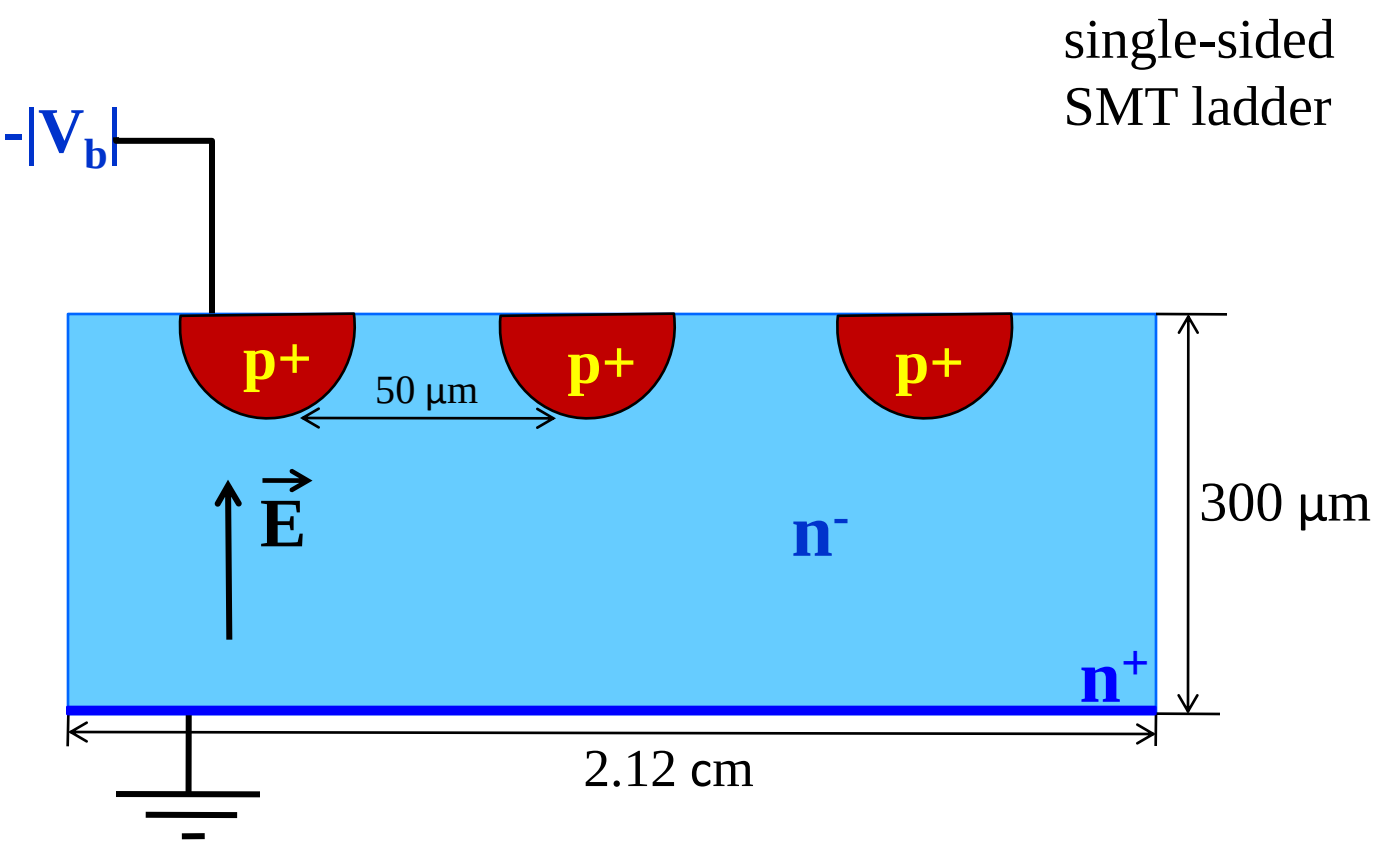
- space charge in the bulk
- boundary conditions

depletion width

$$E(x) = -\frac{q_e N_d}{\varepsilon}(W - x) \equiv E_0(W - x)$$

distance from
the junction

How Detector Works



$$\frac{d^2V}{dx^2} + \frac{Nq_e}{\varepsilon} = 0$$

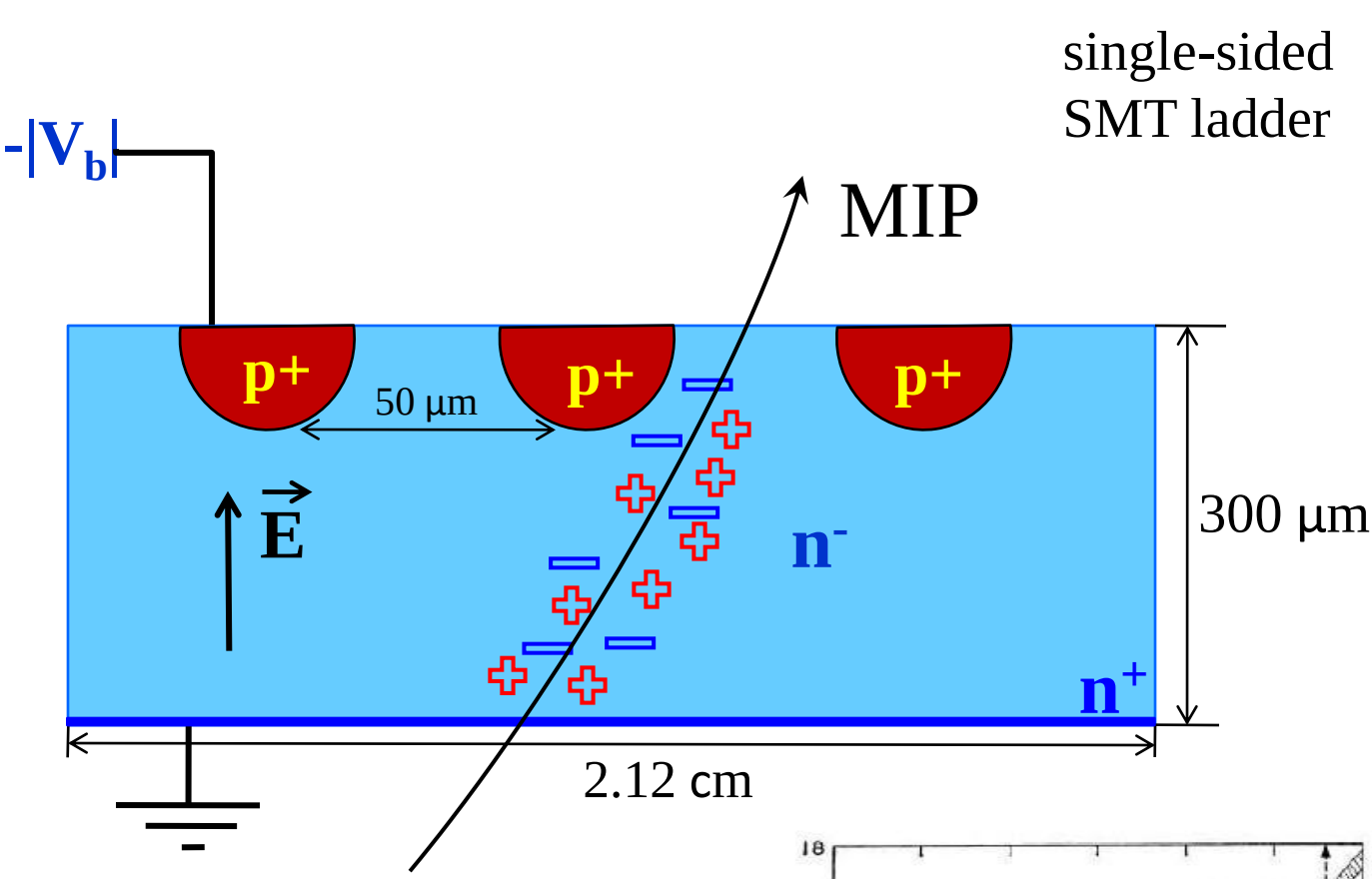
- space charge in the bulk
- boundary conditions

depletion width $W \approx x_n = \sqrt{\frac{2\varepsilon V_b}{q_e N_d}}$ ← donor concentration

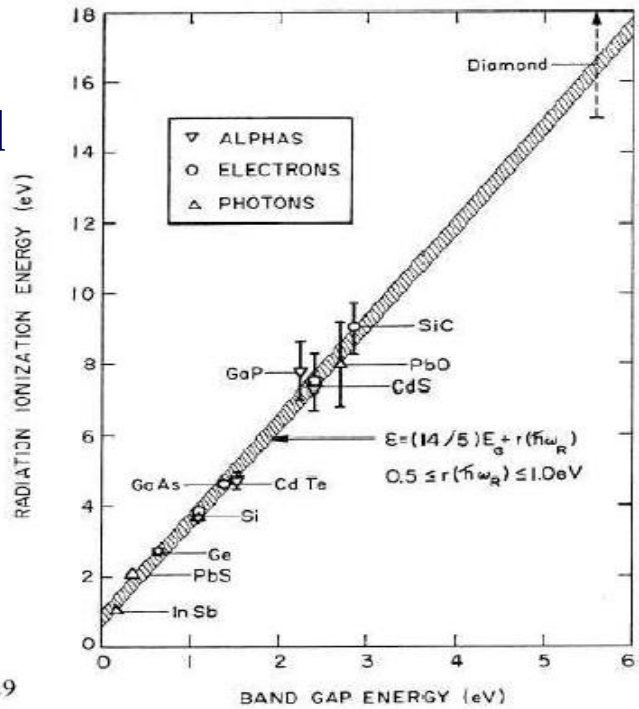
$$E(x) = -\frac{q_e N_d}{\varepsilon}(W - x) \equiv E_0(W - x)$$

distance from the junction

How Detector Works

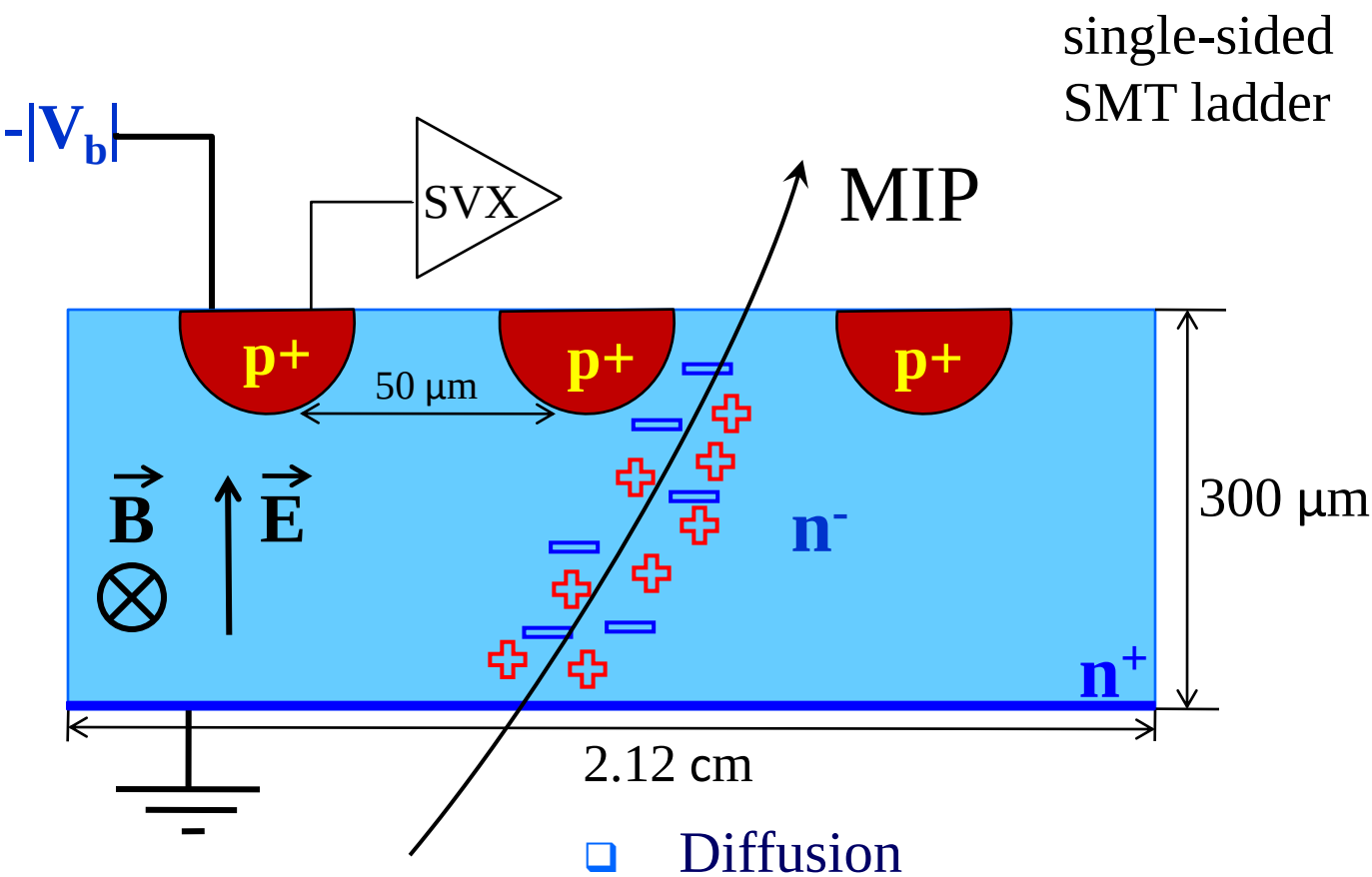


- O(100keV) energy deposited
- ≈30000 electrons created
  - $\times 10^3$ (same size intrinsic Si)
  - ÷10-20 (noise)



C.A. Klein, J. Applied Physics **39** (1968) 2029

How Detector Works



- Diffusion
- Repulsion
- Drift in the magnetic filed
- Drift in the electric field

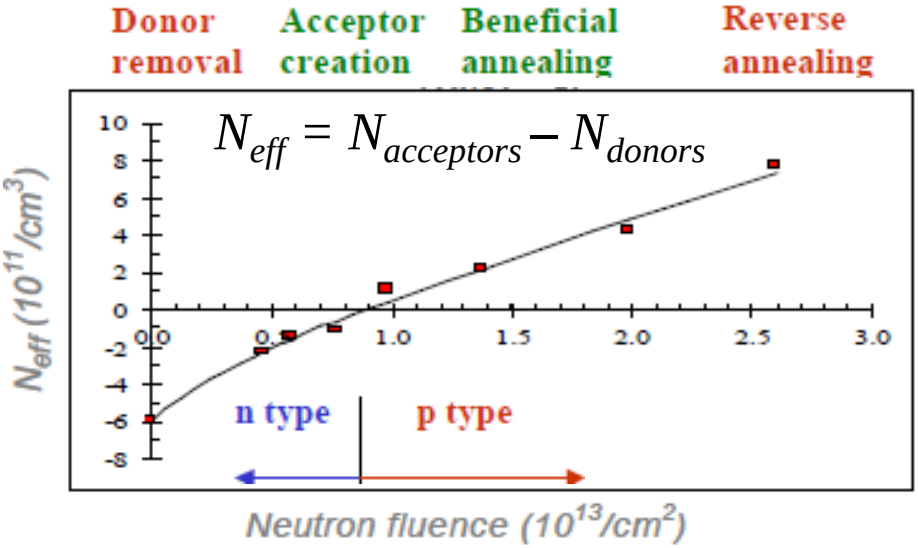
- Charge collection
- ADC output

Radiation Damage

Radiation Damage - Reverse annealing

SSC studies found a complex radiation induced "acceptor generation" effect. Sensitive to time and temperature

$$Neff = -N_0 e^{-c\Phi} + g_c(\Phi) + g_s \Phi e^{-t/\tau(T)} - N_y(\phi, \tau, T)$$



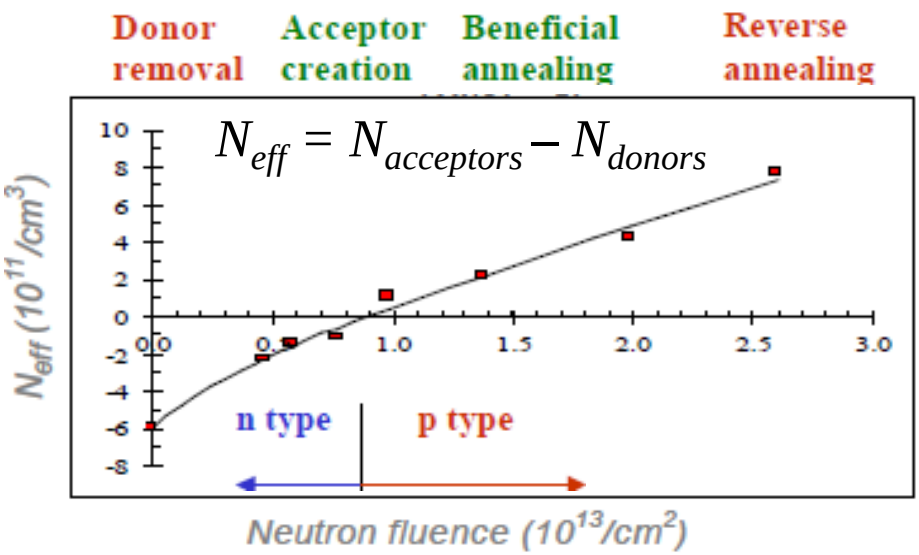
R. Lipton
March 1,8 2000

Radiation Damage (Cont'd)

Radiation Damage - Reverse annealing

SSC studies found a complex radiation induced "acceptor generation" effect. Sensitive to time and temperature

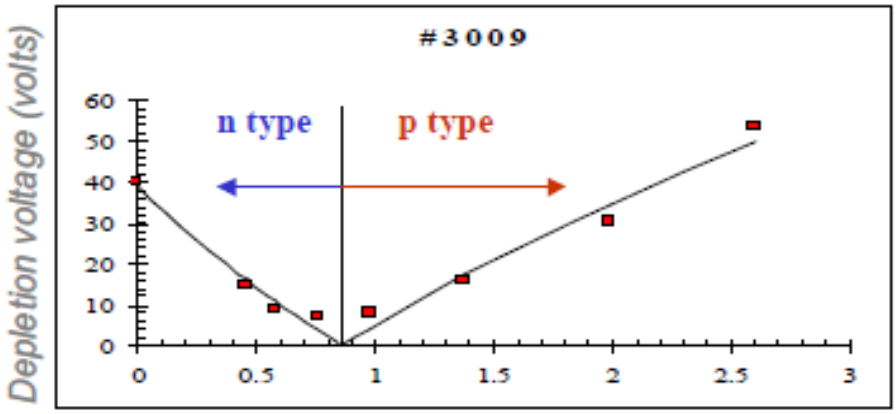
$$Neff = -N_0 e^{-c\Phi} + g_c(\Phi) + g_s \Phi e^{-t/\tau(T)} - N_y(\phi, \tau, T)$$



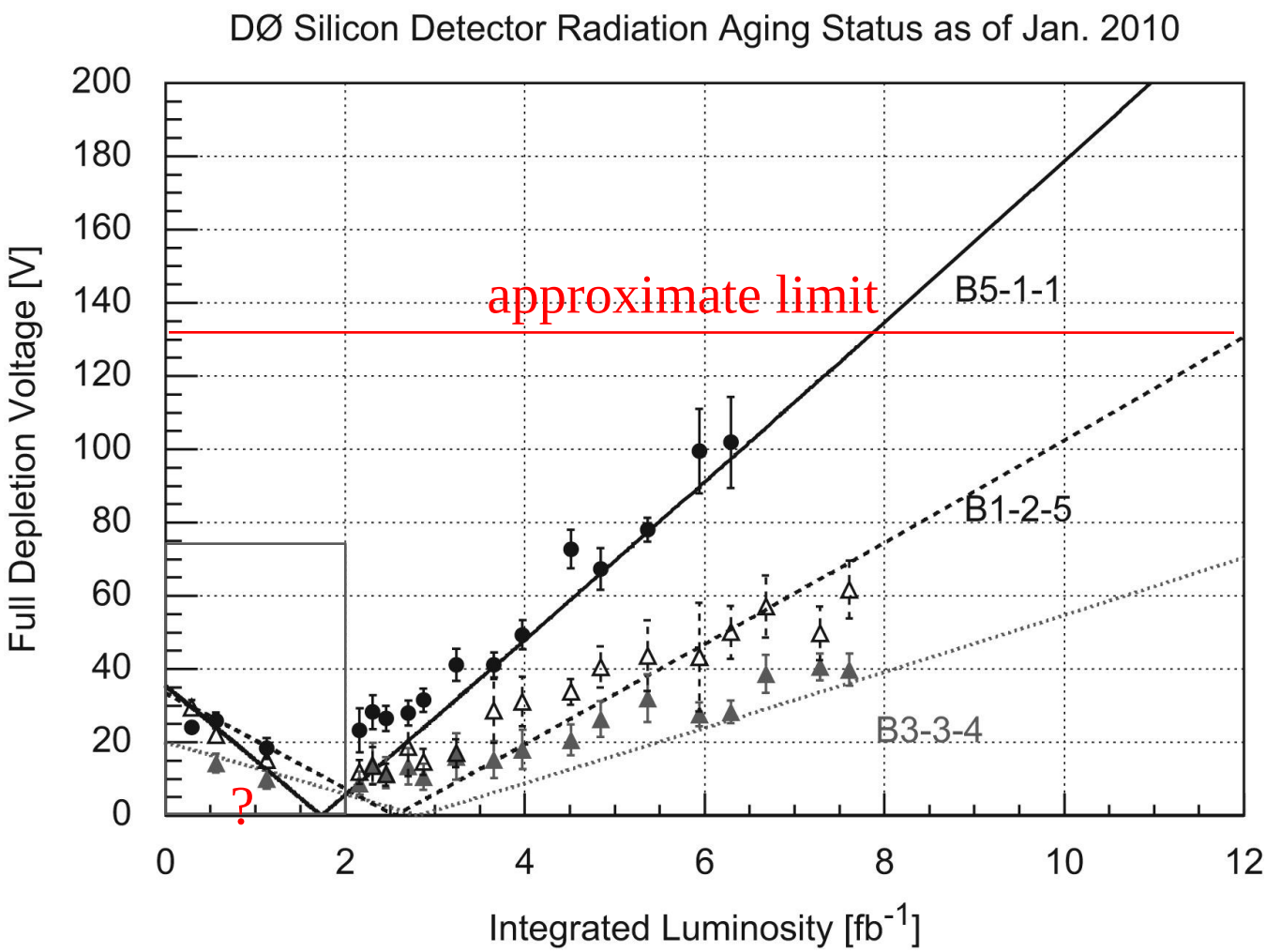
R. Lipton
March 1,8 2000

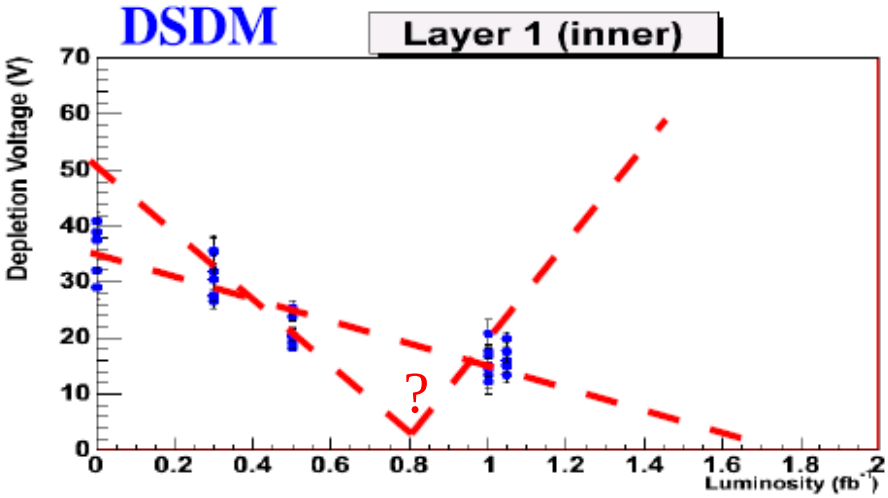
$$W \approx x_n = \sqrt{\frac{2\varepsilon V_b}{q_e N_d}}$$

Depletion Voltage



Depletion Voltage versus Integrated Luminosity





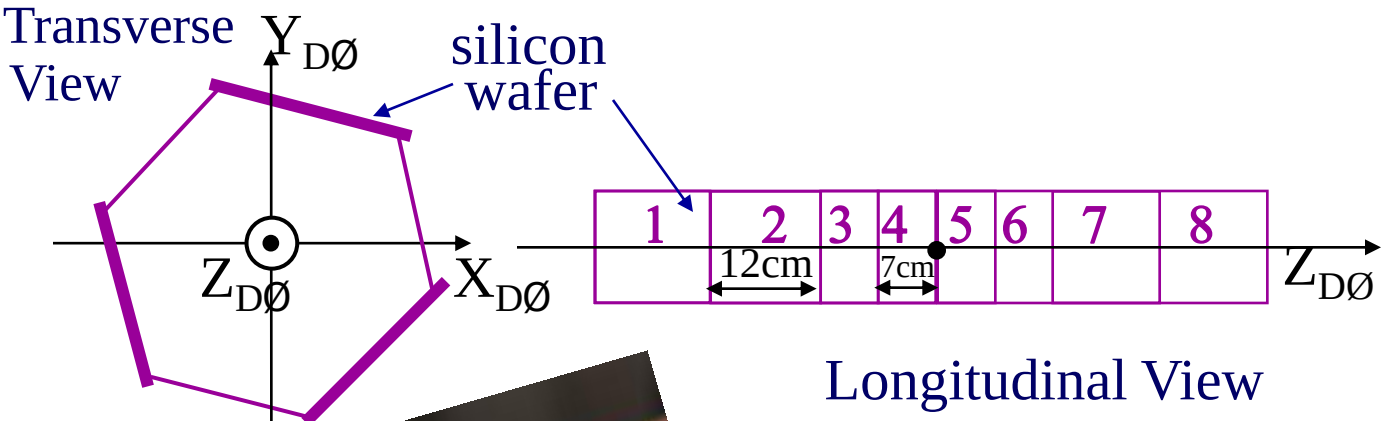
at the time of Layer Ø project:

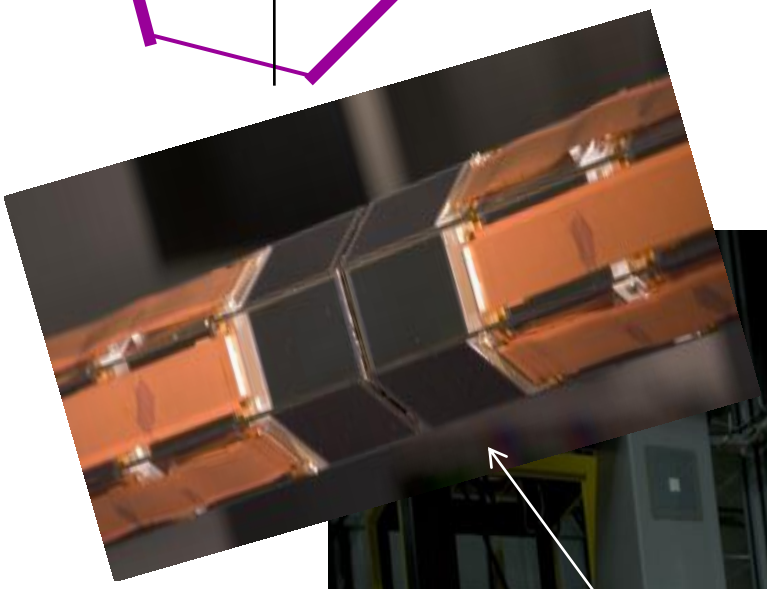
not enough data to distinguish between the two scenarios

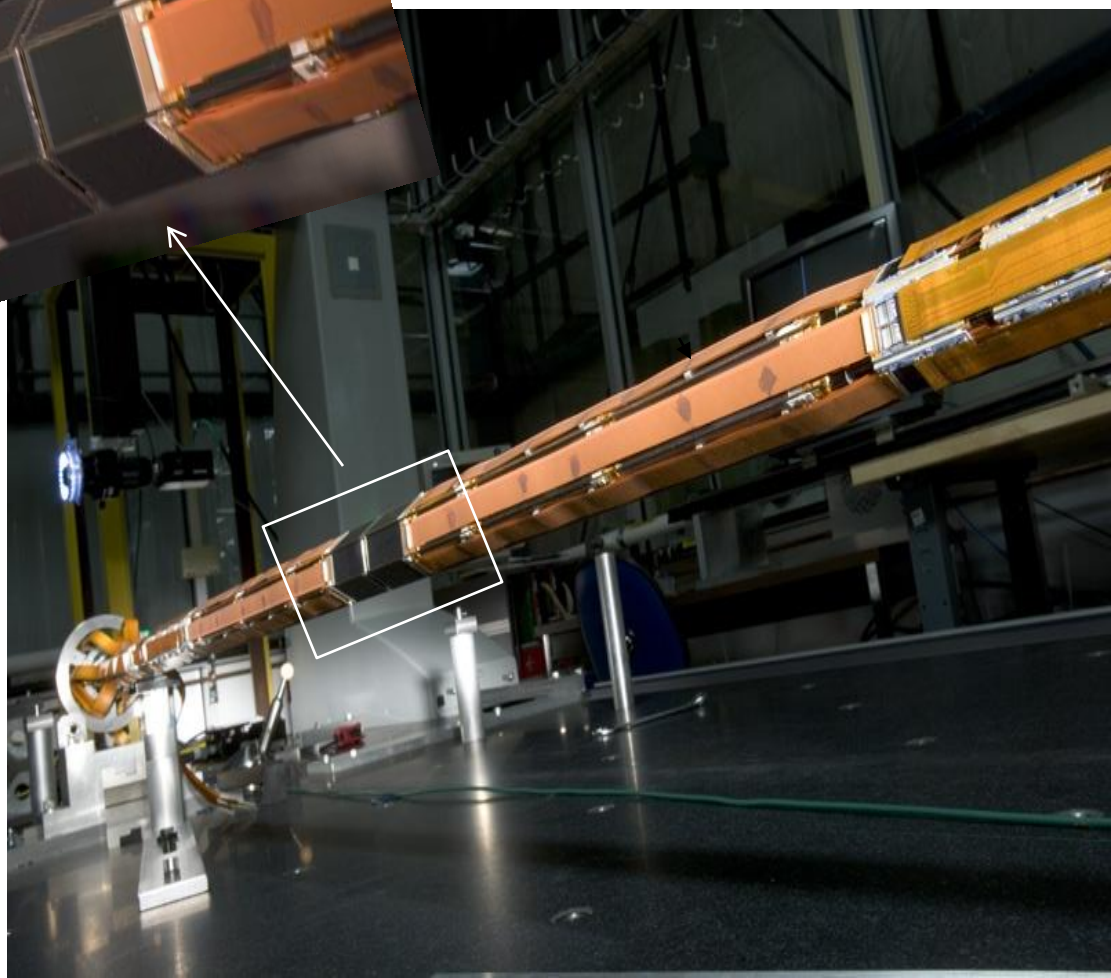
Part 3

Layer Ø Detector

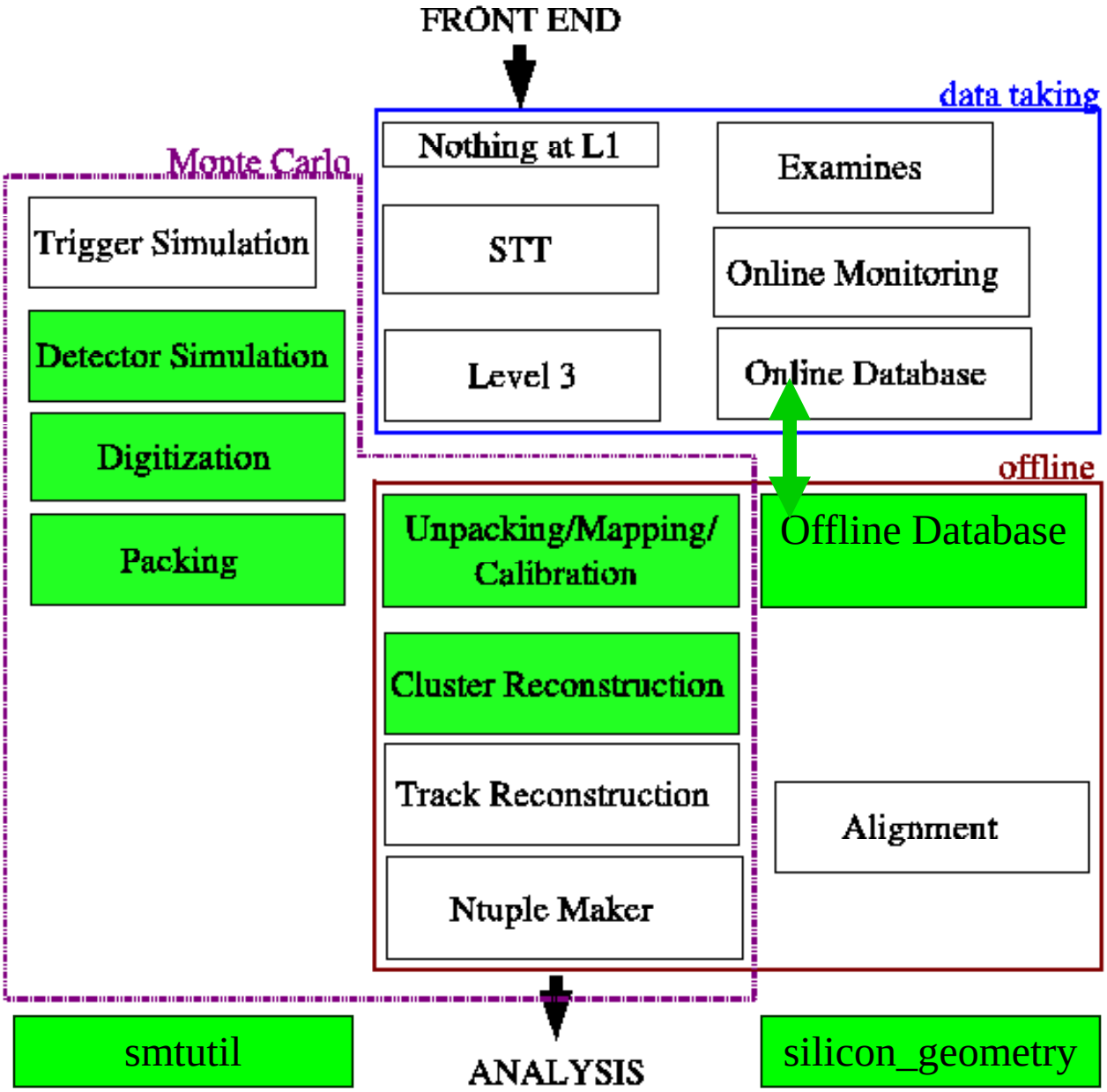
Layer Ø Detector



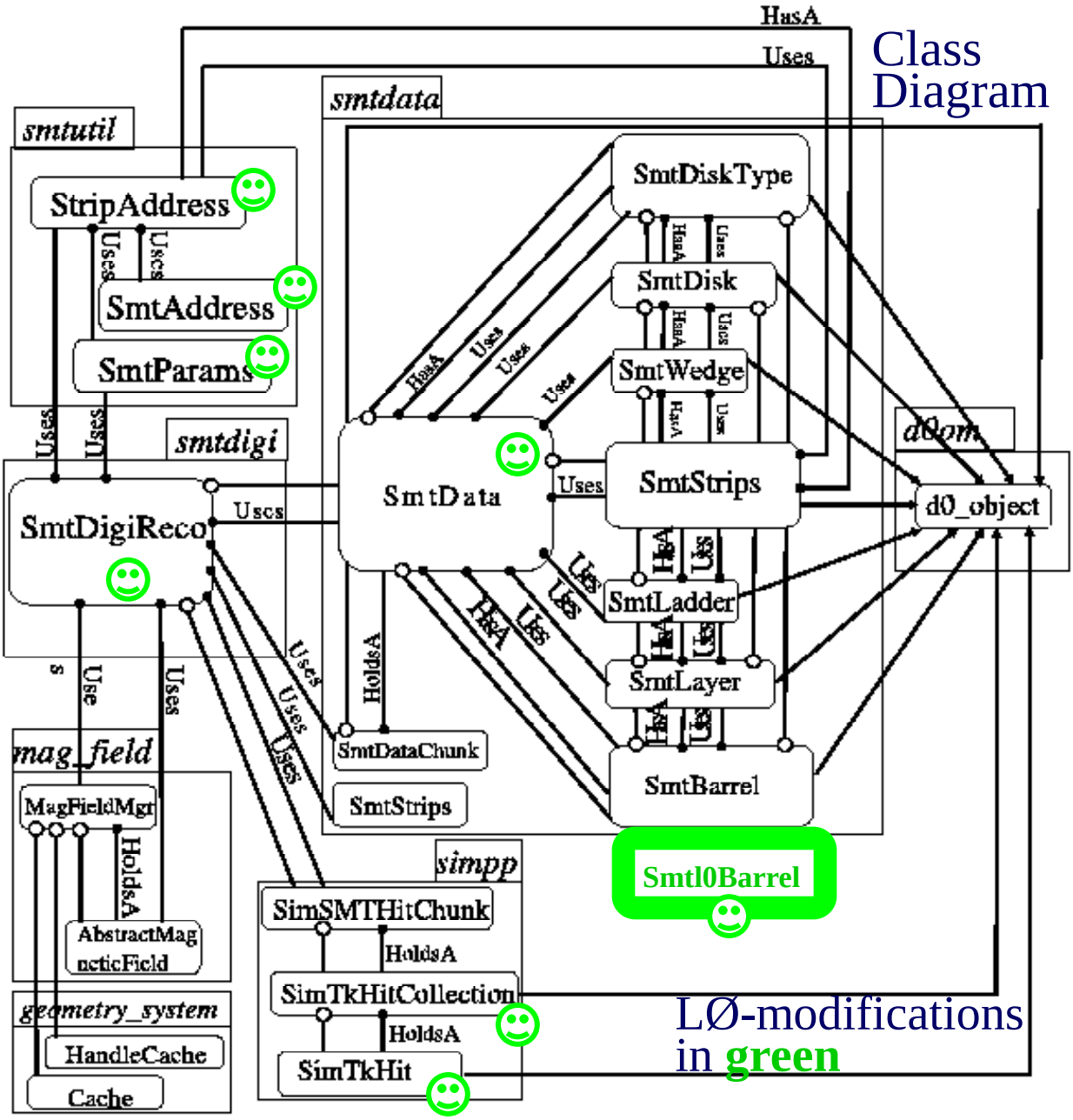




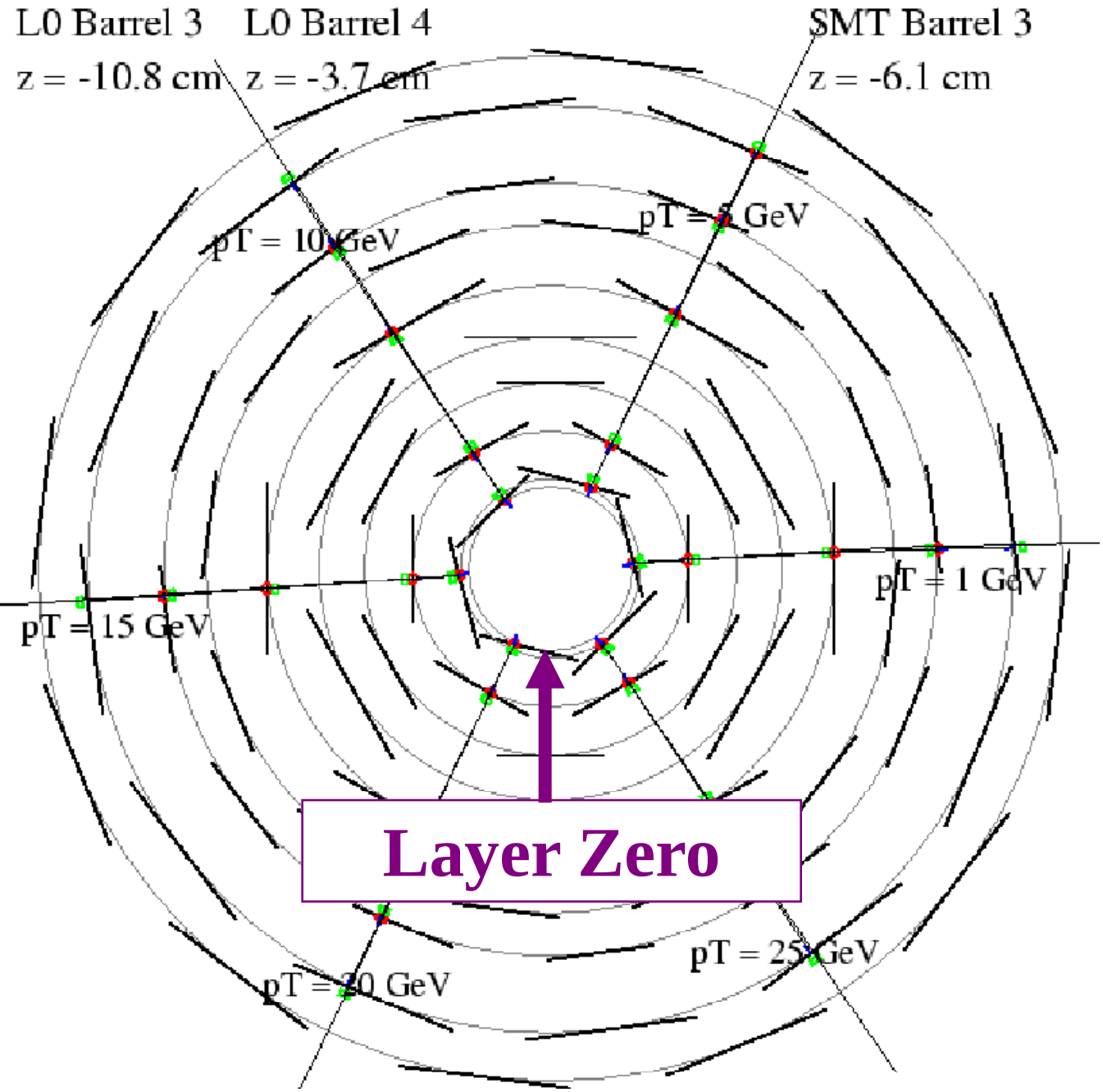
LØ Modifications to the DØ Software



Example: Incorporating LØ into SMT Data Structure



Monte Carlo:
Verifying LØ Performance in the Full DØ Simulation

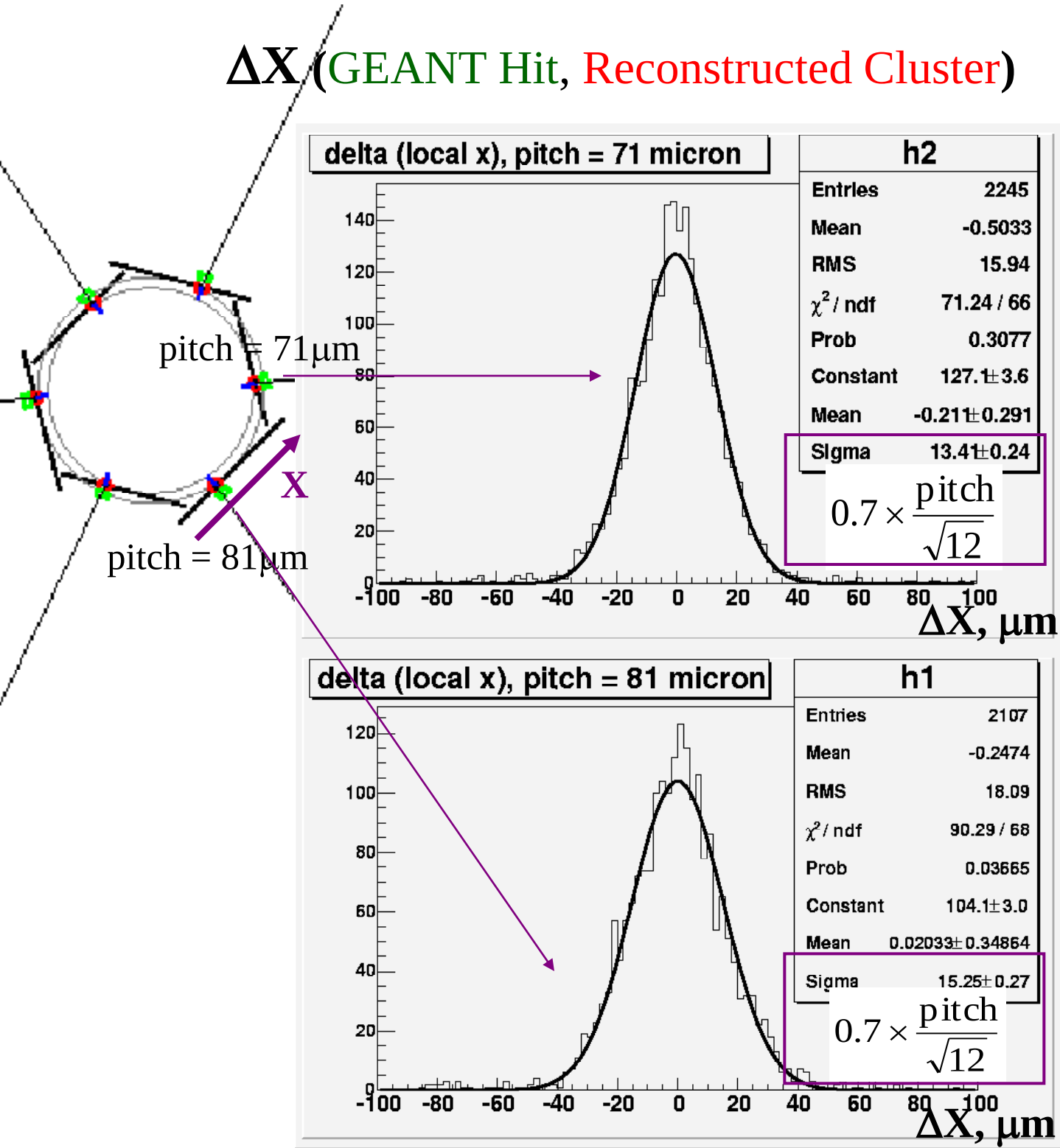


Simulated Hits □ **Reconstructed Clusters** •

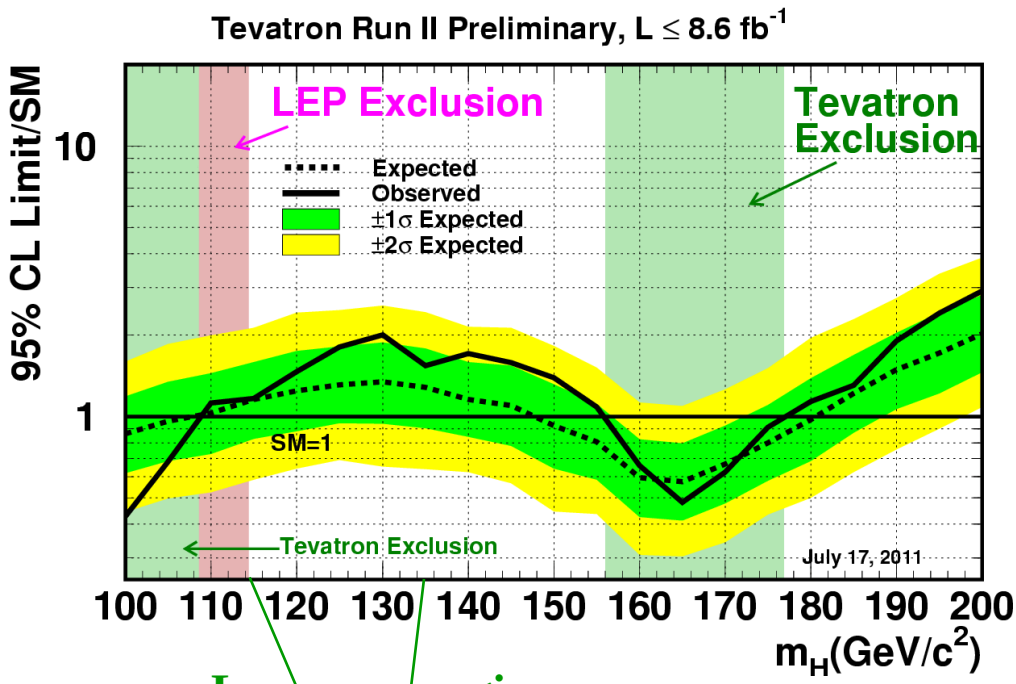
Digitized Hits | **GEANT Tracks** ----------

Hit Position Resolution (Monte Carlo Simulation)

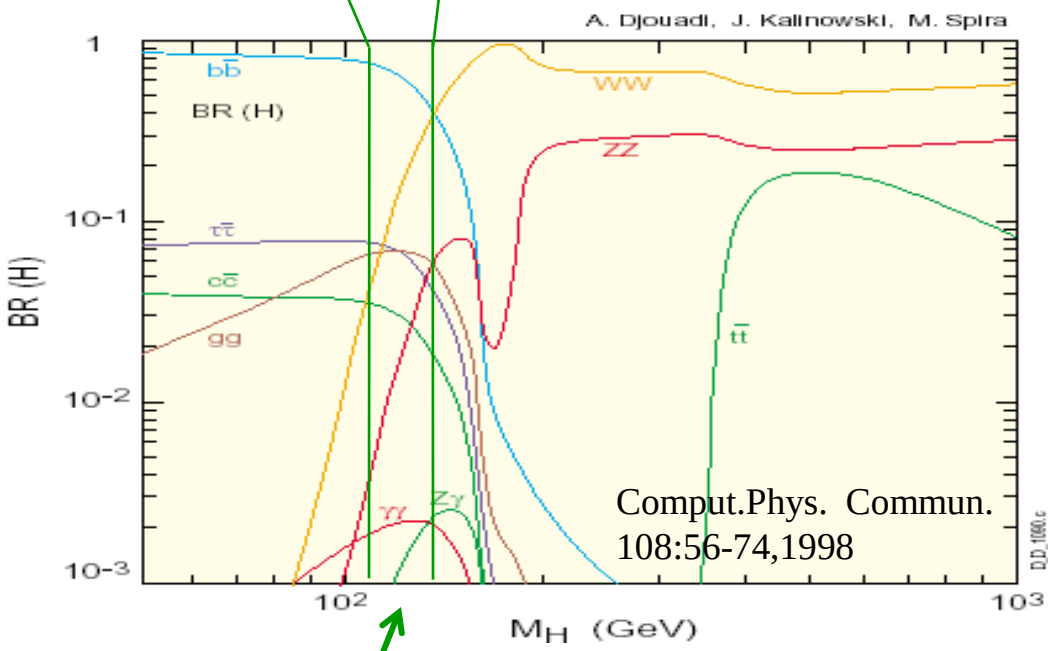
ΔX (GEANT Hit, Reconstructed Cluster)



Layer Ø's Role in Higgs Searches



Low mass region



Higgs decays mostly to b-quarks in low mass region

Higgs Decays at Low Mass

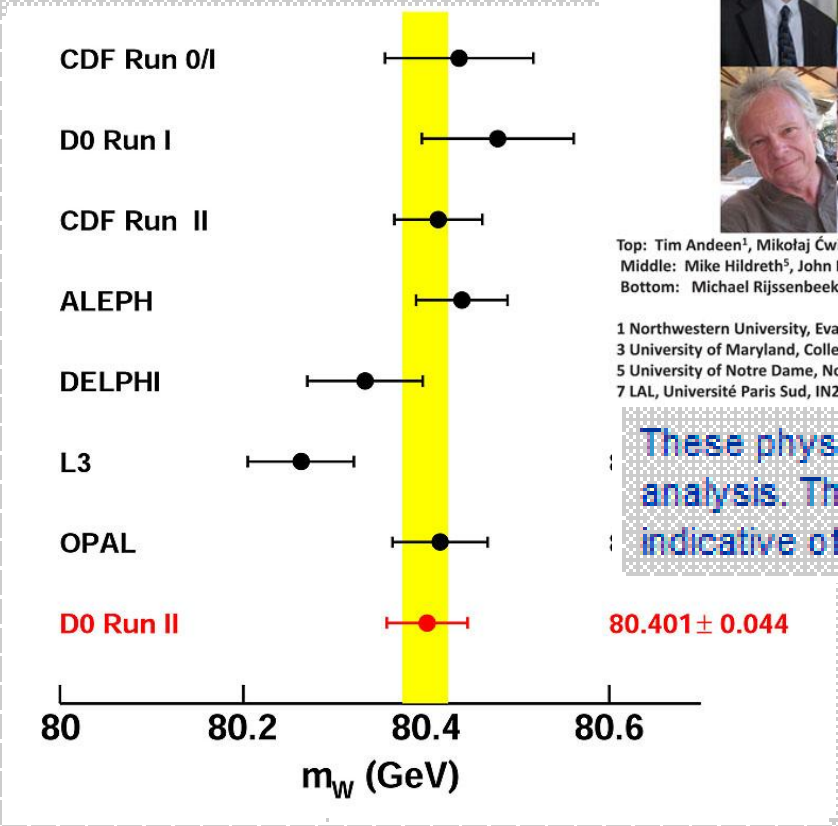
- Signature of $b\bar{b}$ decays: displaced secondary vertex
  - ✓ proper lifetime of a B meson ≈1.5 ps
  - ✓ travels on average half a millimeter before decaying
  - ✓ detecting hits at a small radial distance from the collision point (Layer Ø) is crucial for identifying B decays

DØ W Boson Mass Measurement

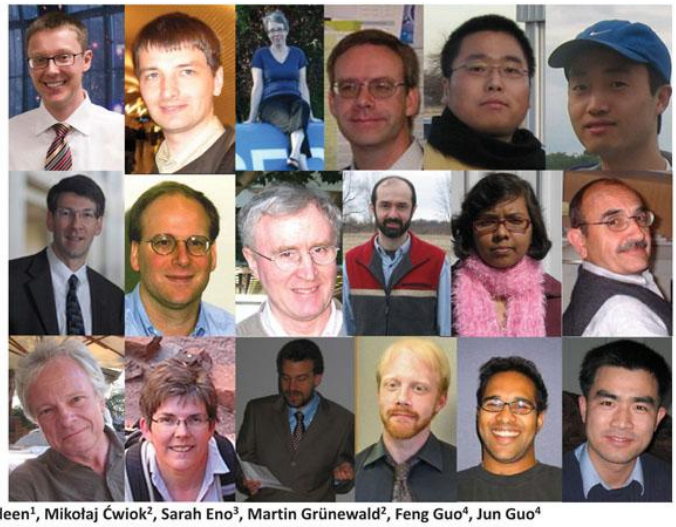
Fermilab Today Thursday, March 19, 2009

Fermilab Result of the Week

Astounding accuracy



DZero collaborators have recently released their extremely precise measurement of the W boson mass. It is the single most precise measurement thus far.



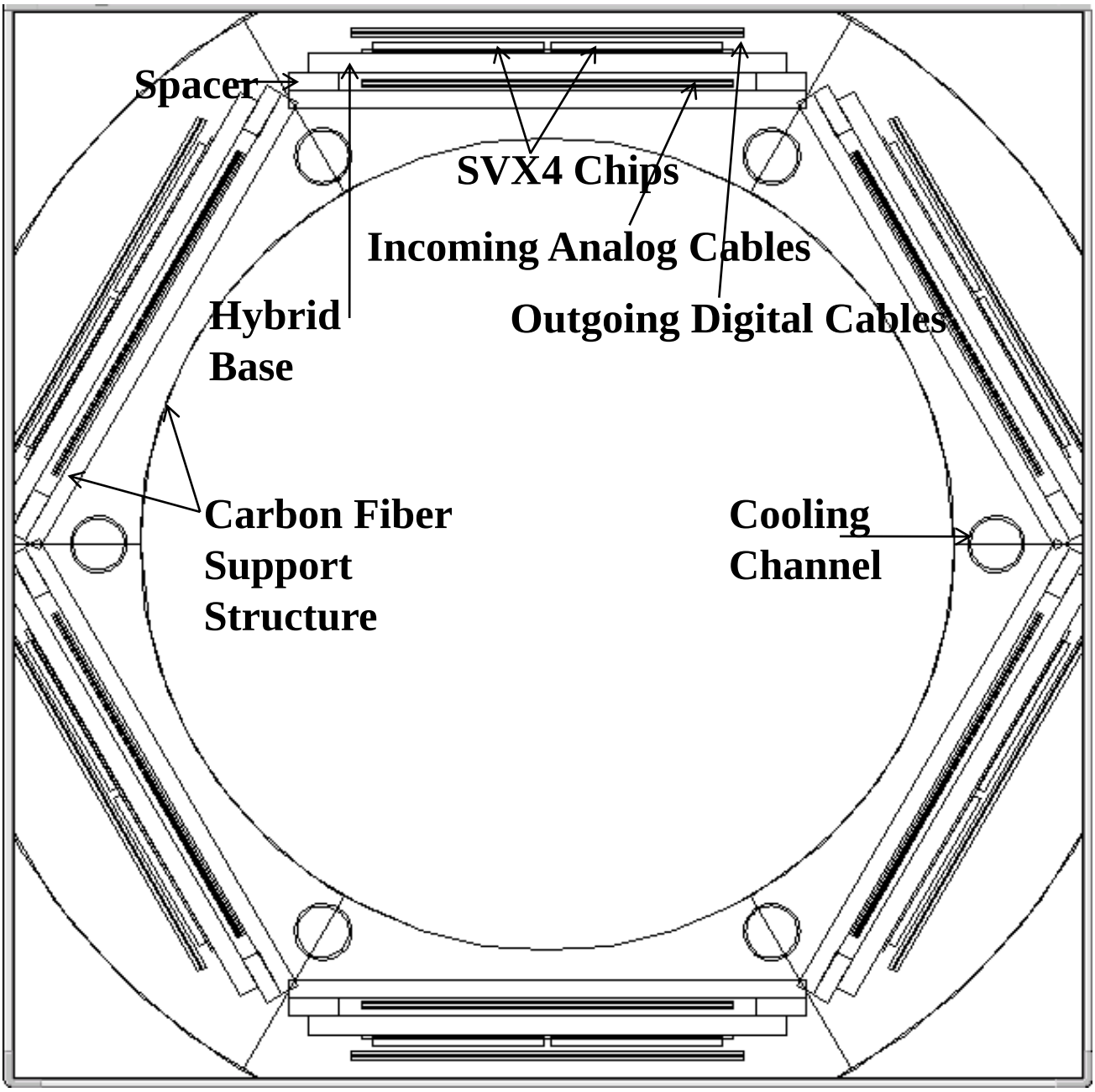
Top: Tim Andeen[1], Mikołaj Ćwiok[2], Sarah Eno[3], Martin Grünewald[2], Feng Guo[4], Jun Guo[4]
Middle: Mike Hildreth[5], John Hobbs[4], Bob McCarthy[4], Alex Melnitchouk[6], Jyotsna Osta[5], Pierre Pétroff[7]
Bottom: Michael Rijssenbeek[4], Heidi Schellman[1], Jan Stark[8], Matt Wetstein[3], Sahal Yacoob[1], Junjie Zhu[4]

1 Northwestern University, Evanston, IL, 60208, USA
2 University College Dublin, Dublin, Ireland
3 University of Maryland, College Park, MD, 20742, USA
4 State University of New York, Stony Brook, NY, 1
5 University of Notre Dame, Notre Dame, IN, 46556, USA
6 University of Mississippi, University, MS, 38677,
7 LAL, Université Paris Sud, IN2P3⊠CNRS, Orsay, France
8 LPSC, Université Fourier, IN2P3⊠CNRS, INPG, Gre

These physicists played a crucial role in this analysis. The large size of the group is indicative of the difficulty of the analysis.

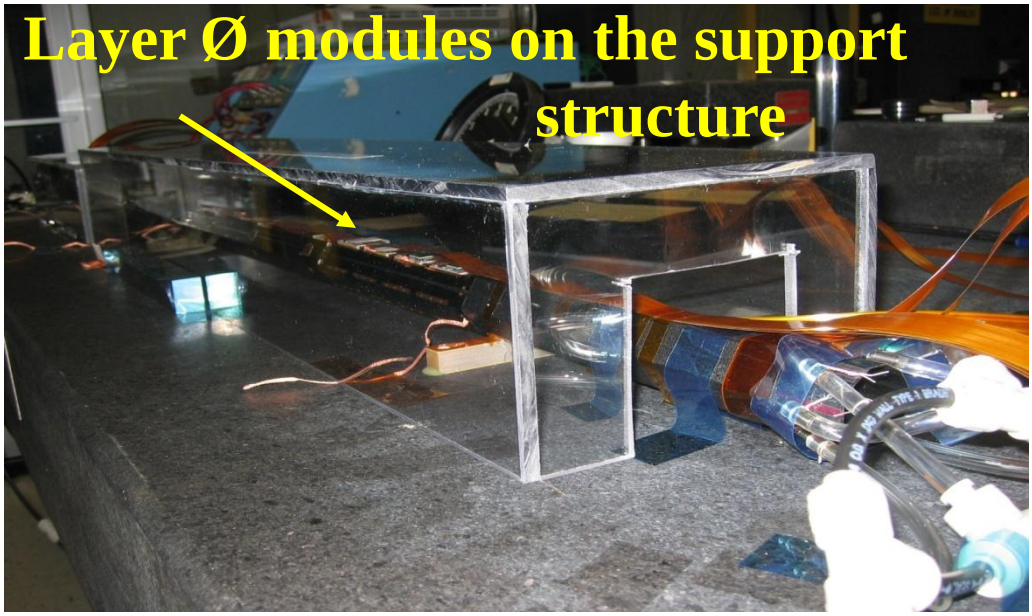
- W boson lives $O(10^{-25}$ s)
- W decay to stable particles ($W \rightarrow e\nu$) is used
- Electron showers in the calorimeter

GEANT View of Simulated Passive Material



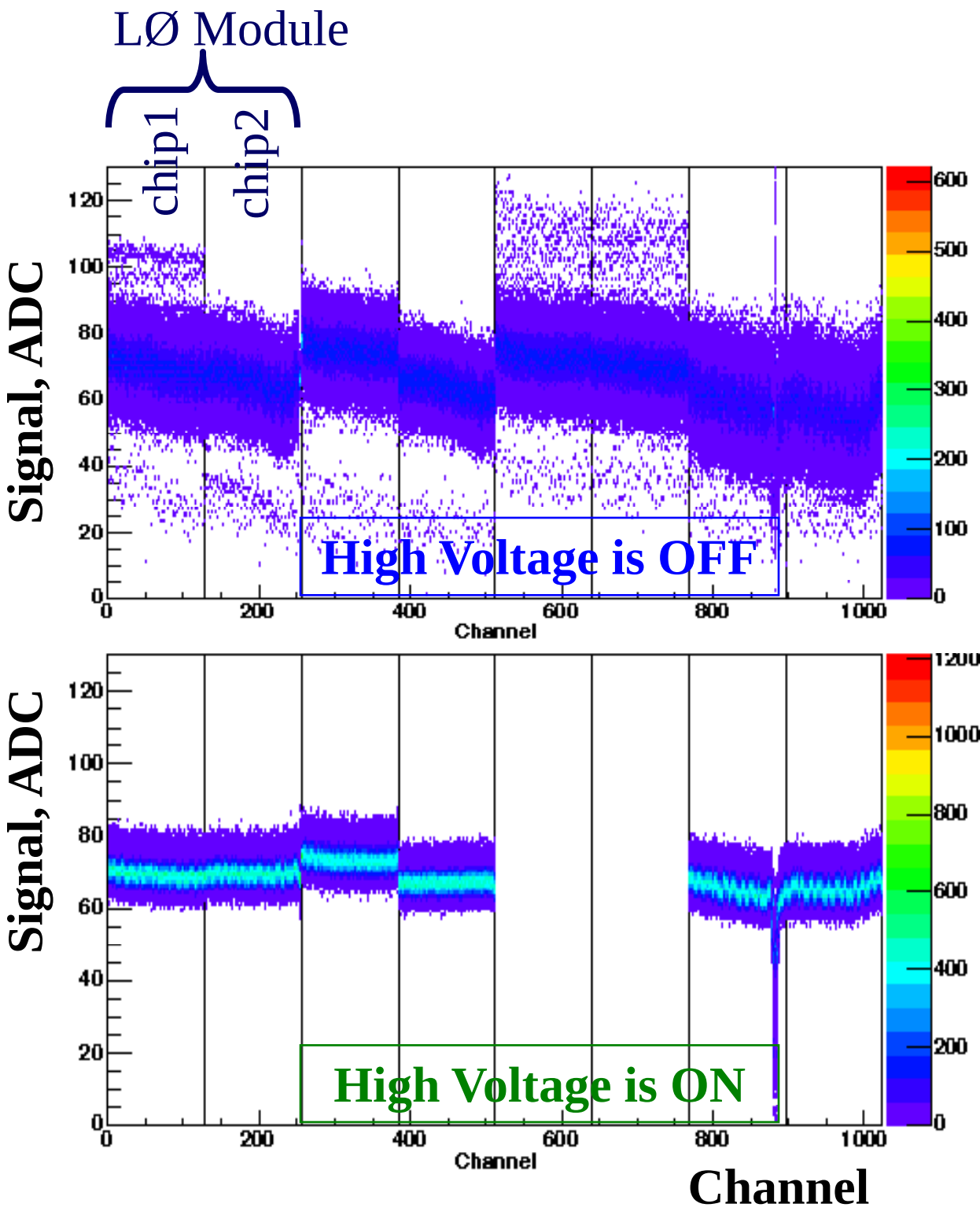
Checking LØ Module Noise Level
(LØ Assembly Site)

Prototype LØ modules mounted on prototype support structure are read out



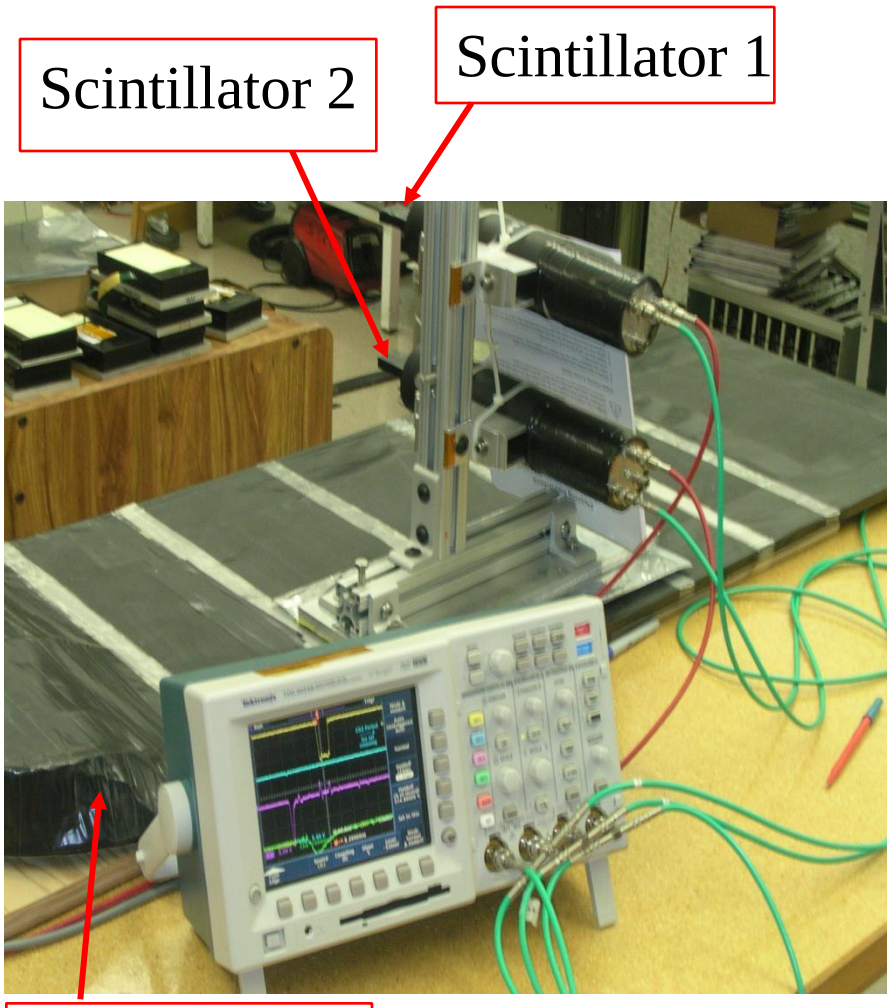
Then data are converted to the standard DØ data format, and processed with offline DØ software

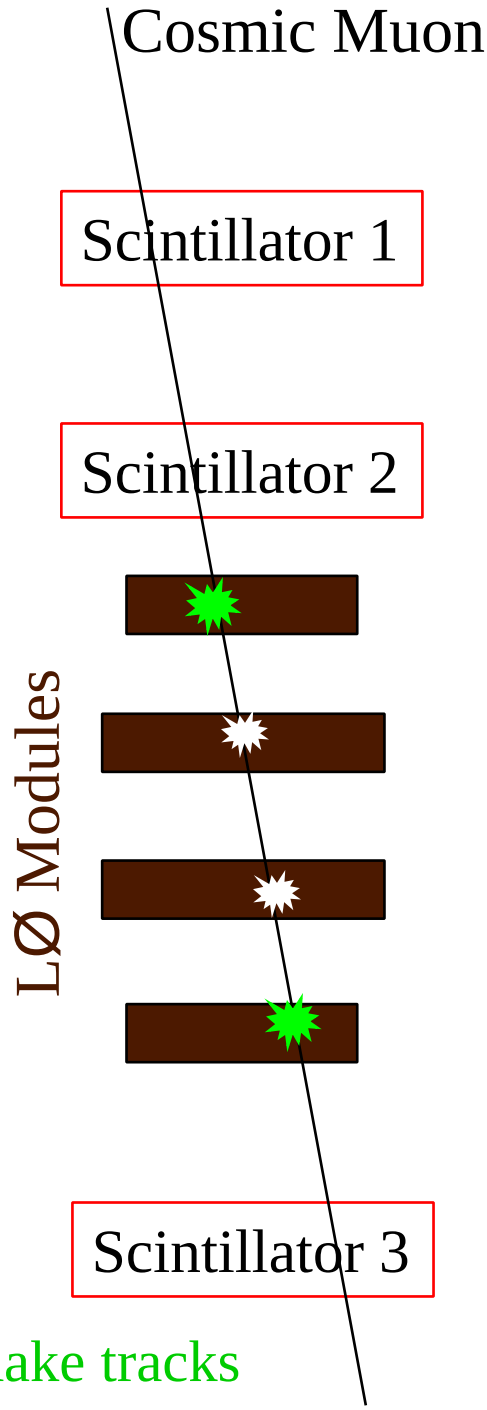
Testing LØ Modules



LØ Cosmic Muon Test
(LØ Assembly Site)

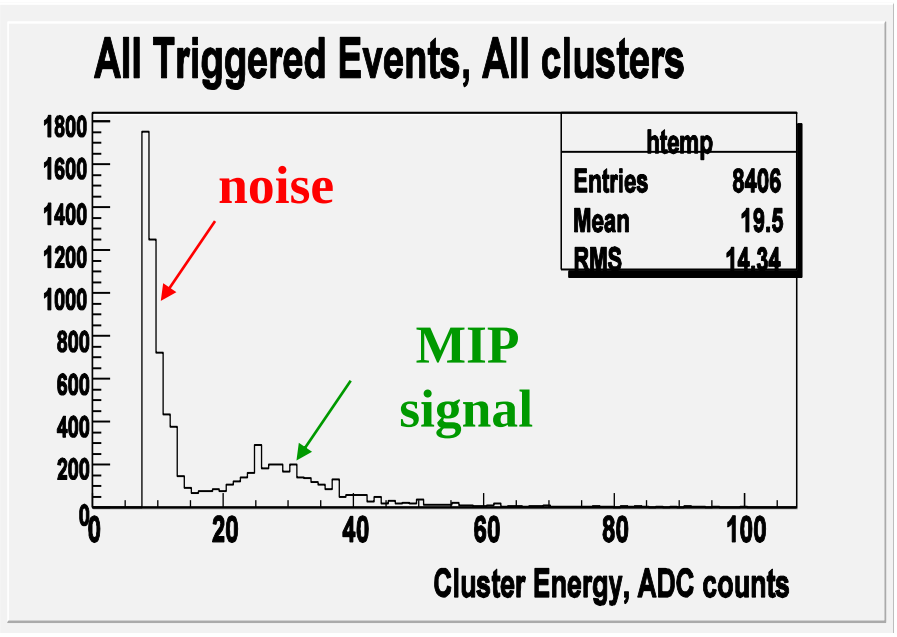
- trigger when all three scintillators have signal

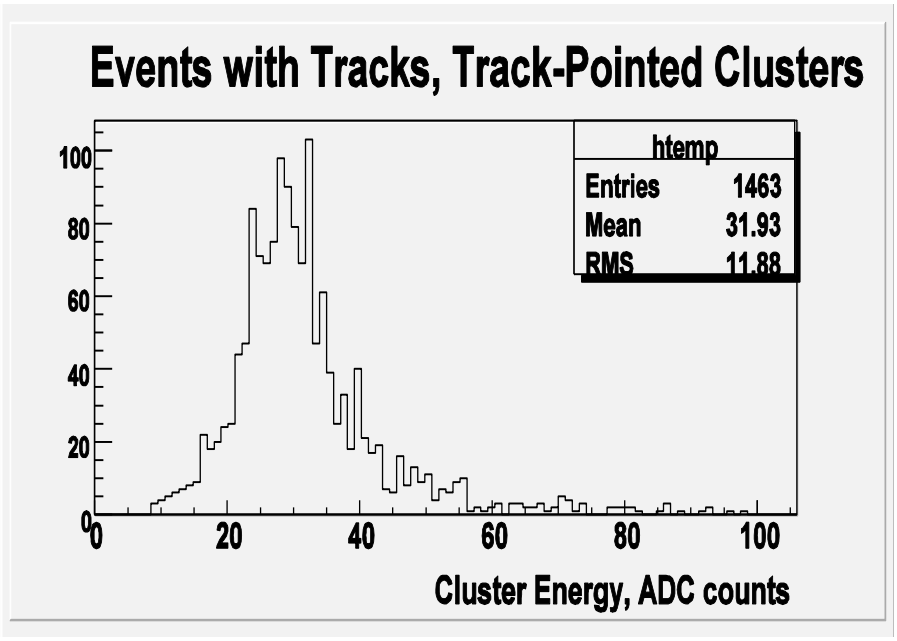


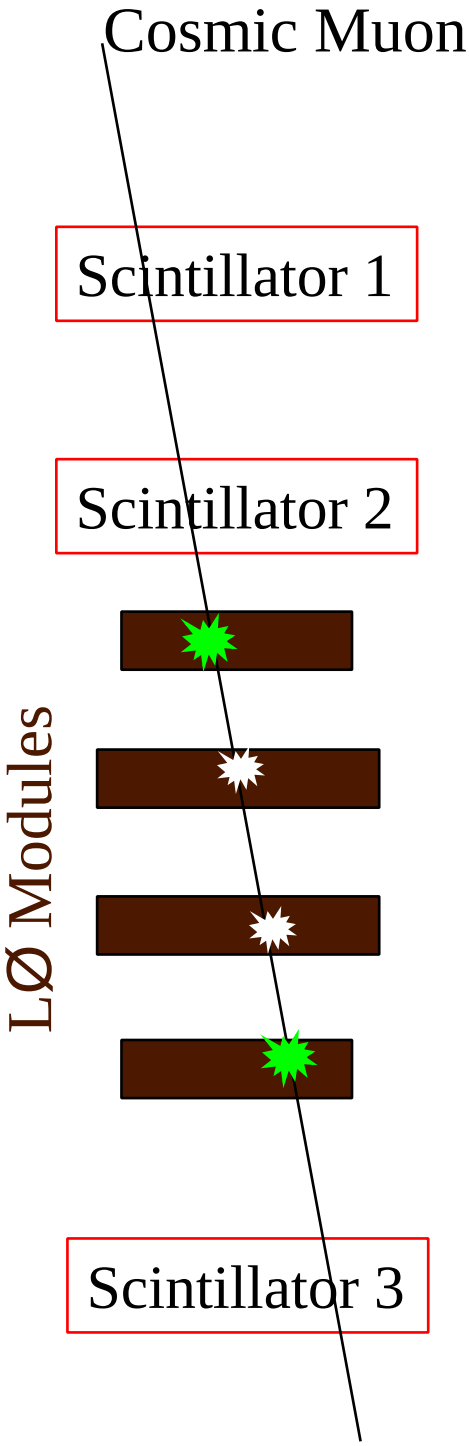


- use clusters in outer modules – make tracks
- study track-pointed clusters in the inner modules

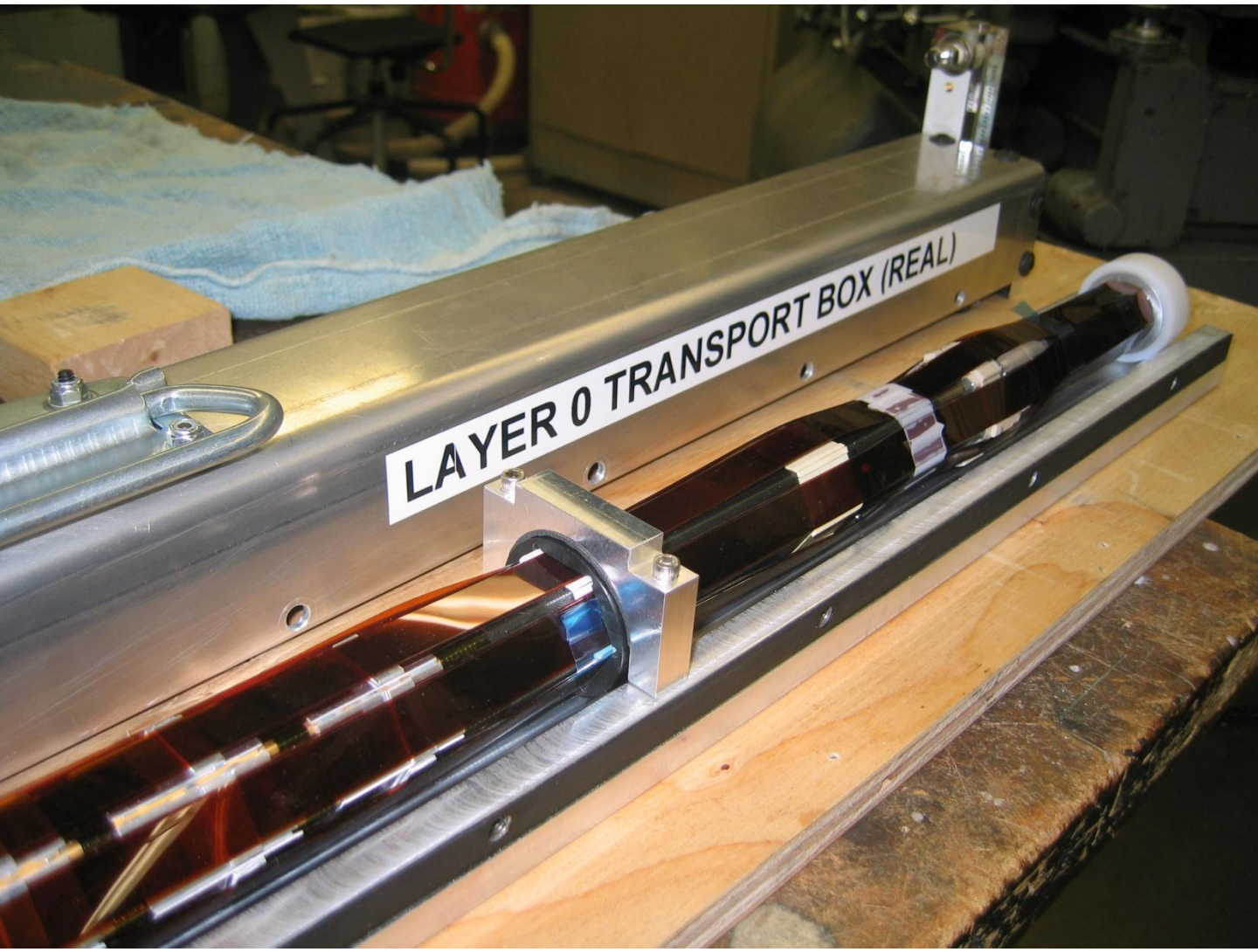
Clustered Energy in LØ Modules



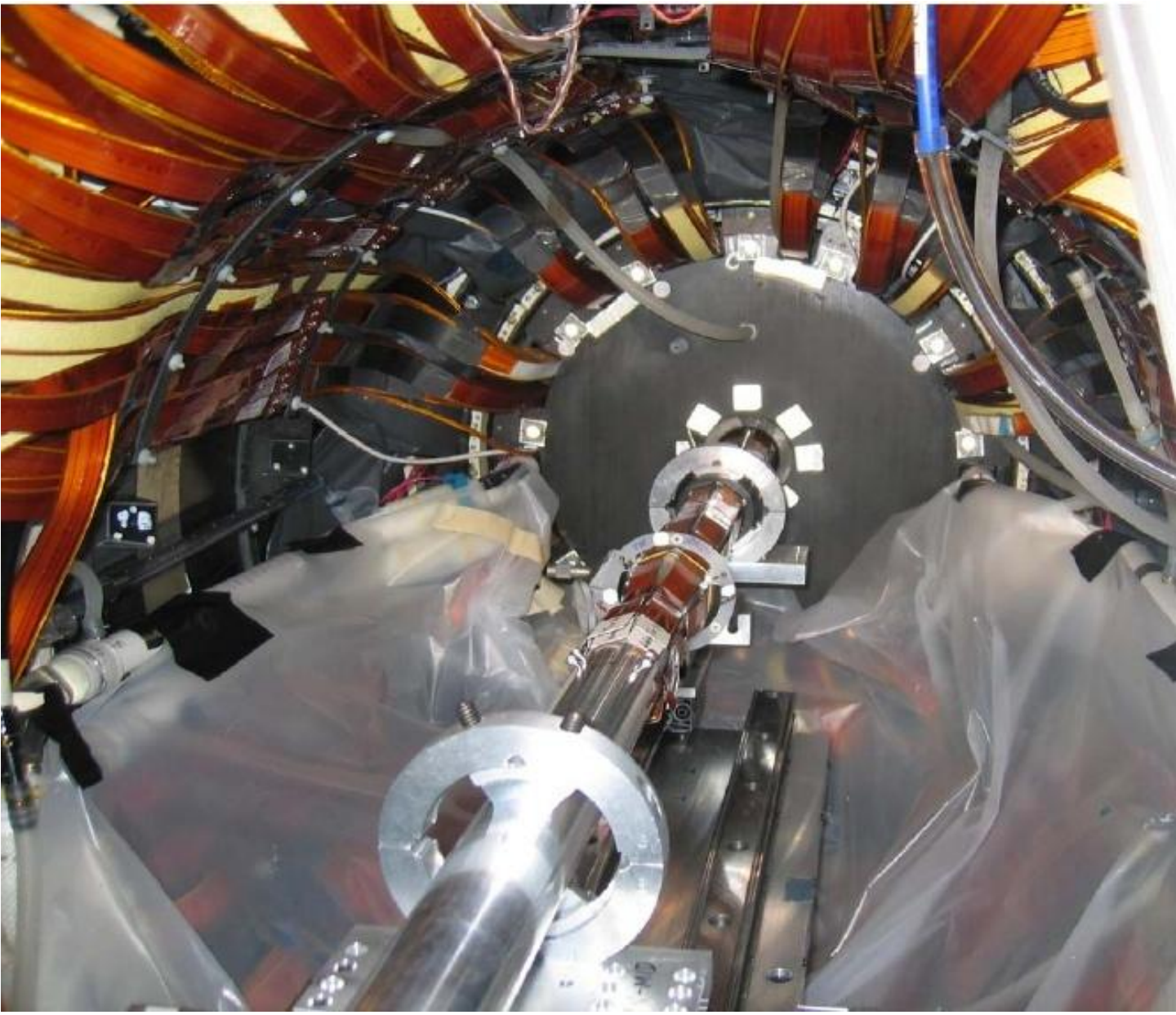




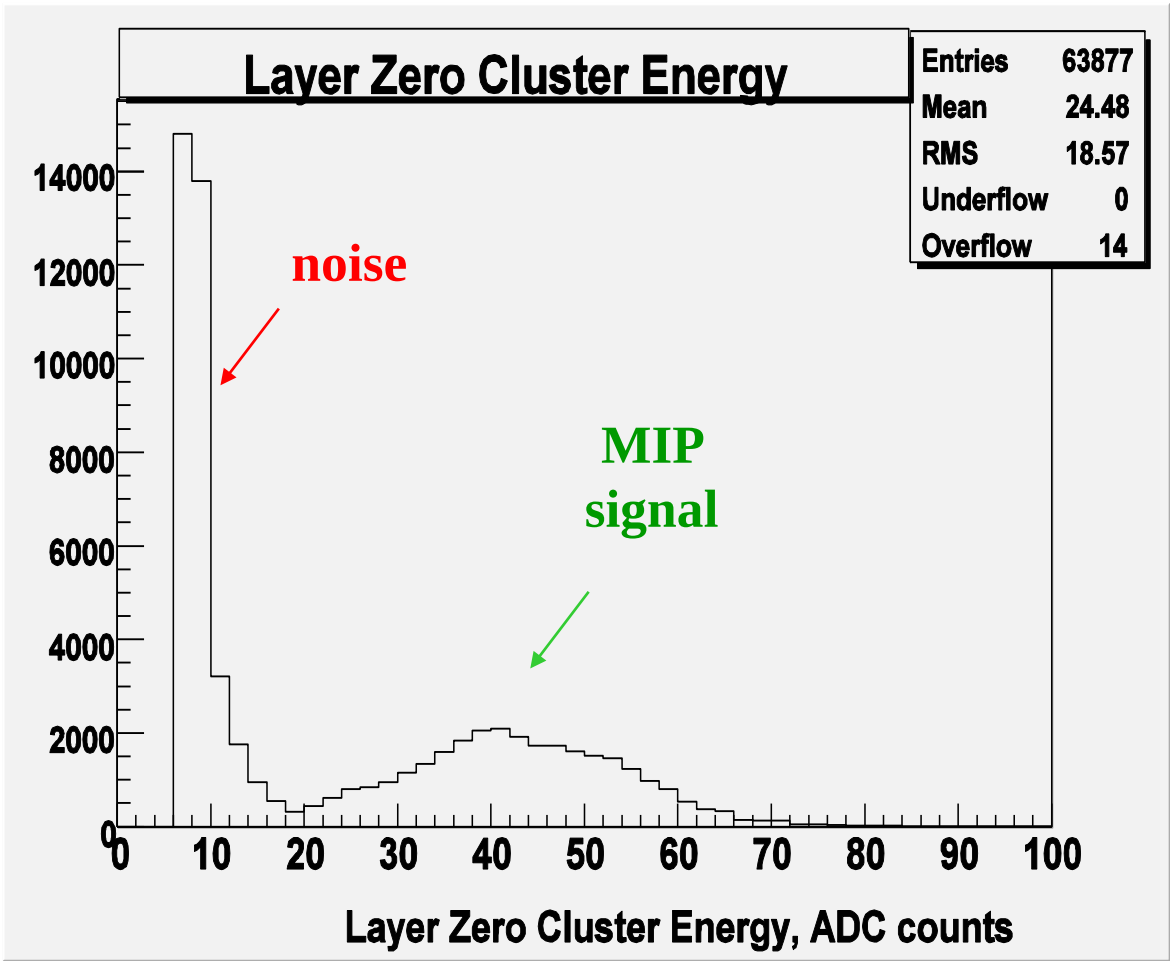
Layer Ø is Ready



Layer Ø goes in !
(Spring 2006 Tevatron Shutdown)



Layer Ø Cosmic Muon Data
(DØ Collision Hall)



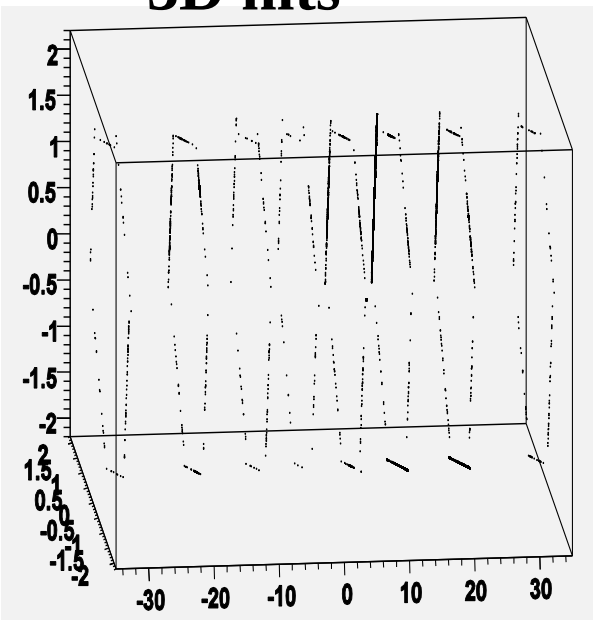
Observed Data have the Right Shape !

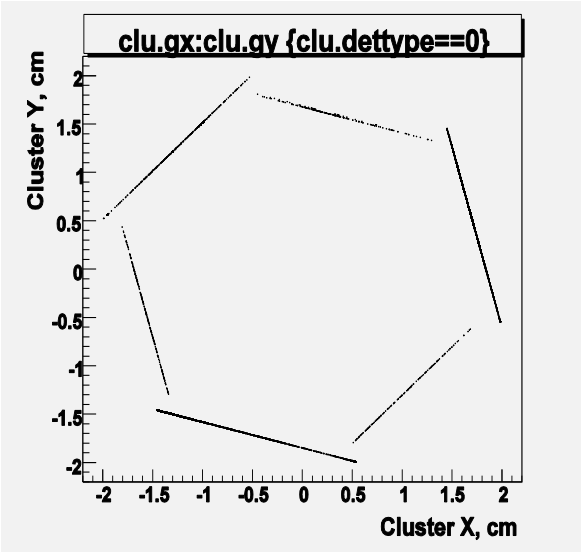
... coming from where exactly in the detector ?

Muon "X-Ray" Picture of Layer Ø (DØ Collision Hall)

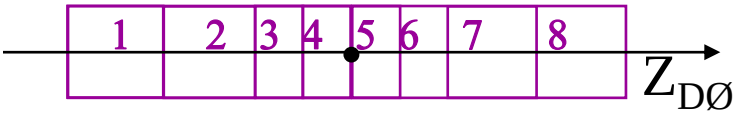
Project to XY

3D hits



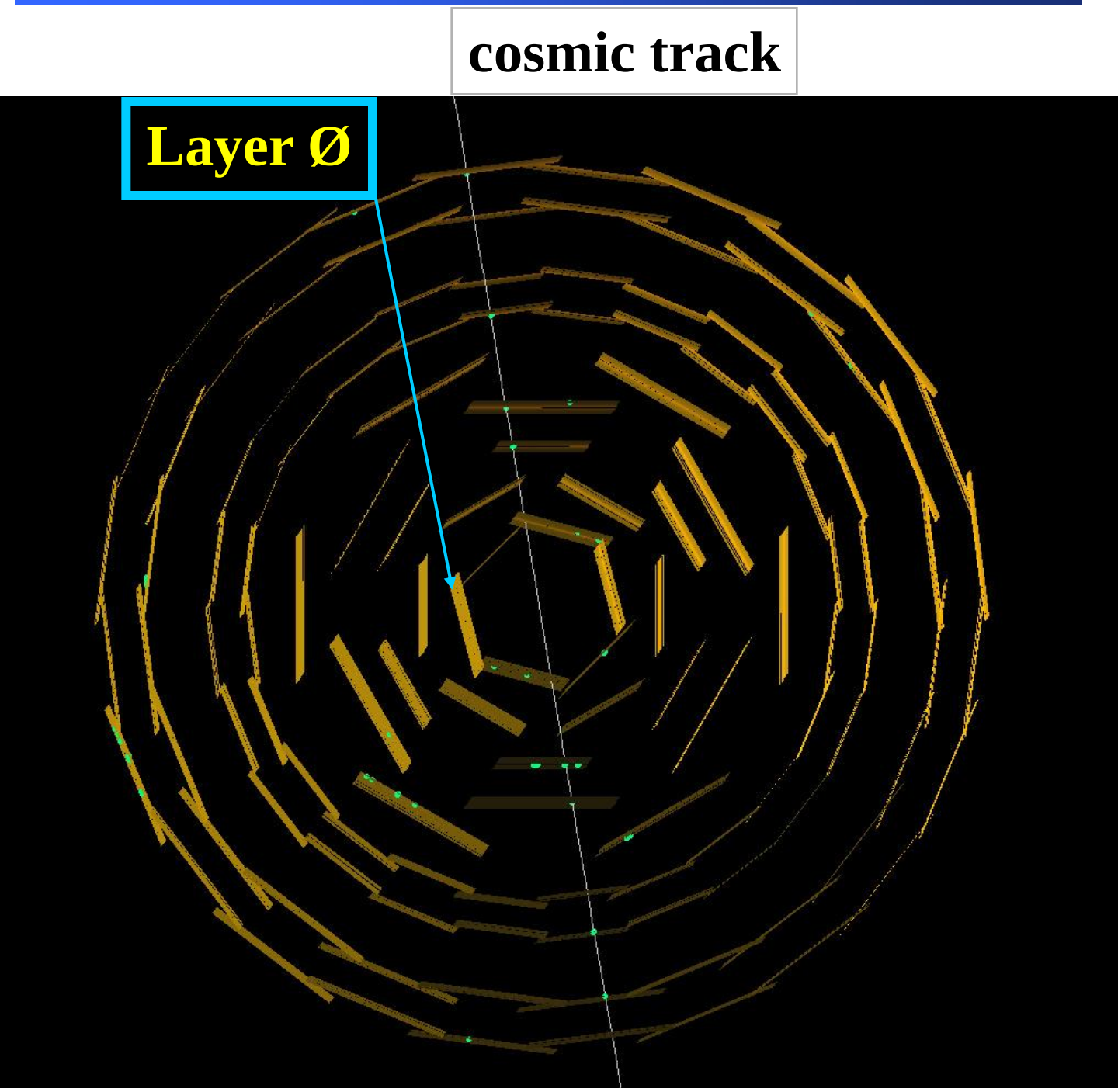


Global Z
discrete values
for Layer Ø barrel locations



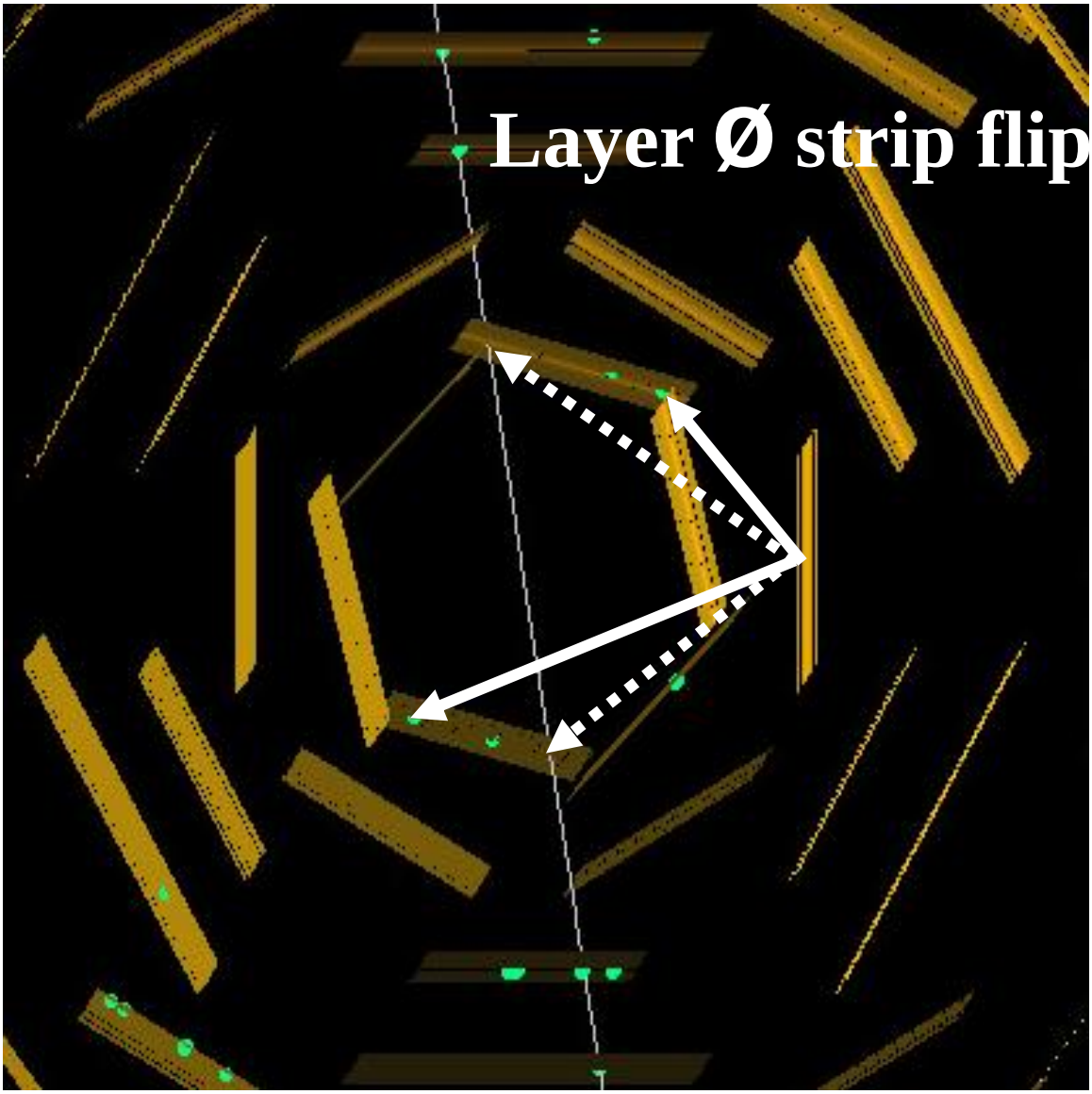
... from the Right Locations !

Reconstructing Tracks



first look at DØ cosmic data suggested that Layer Ø channels are flipped

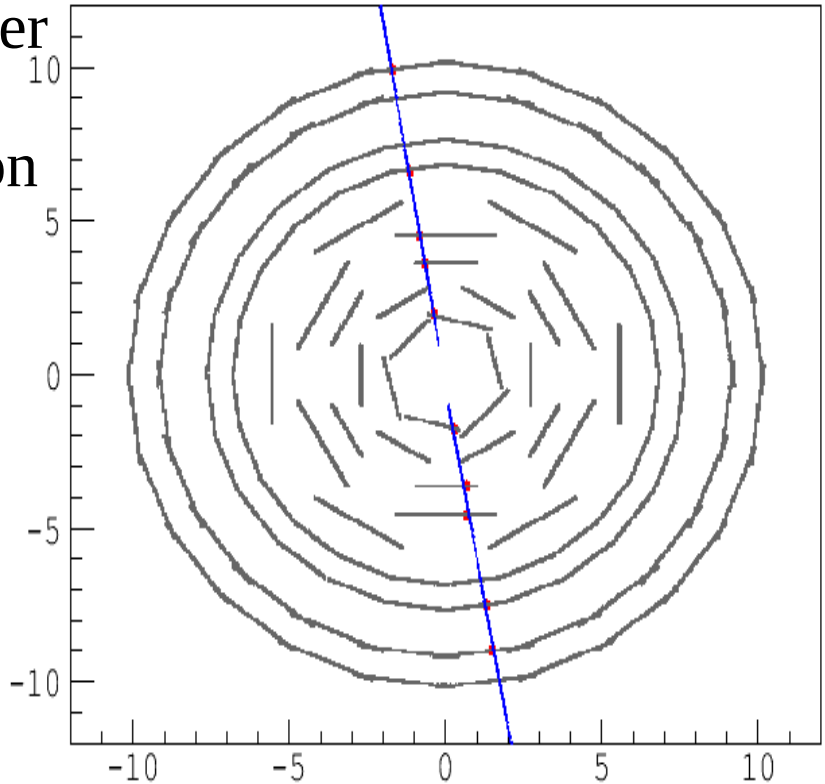
Initial Channel Flip in Layer Ø Software



Event Display with a Cosmic Track (channel flip fixed)

Offline Track Reconstruction

Level 2 Trigger Track Reconstruction



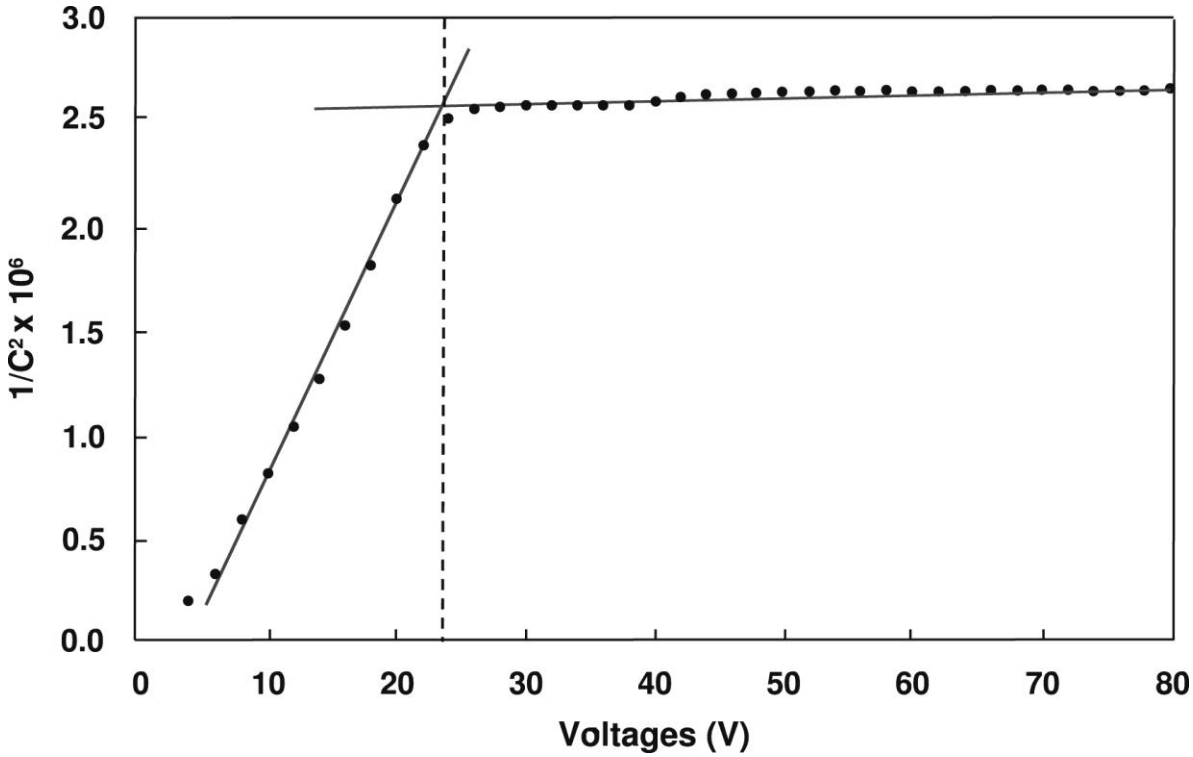
using cosmic data, the software was debugged and prepared for collisions, including first pass tracker alignment

This presentation borrowed material from

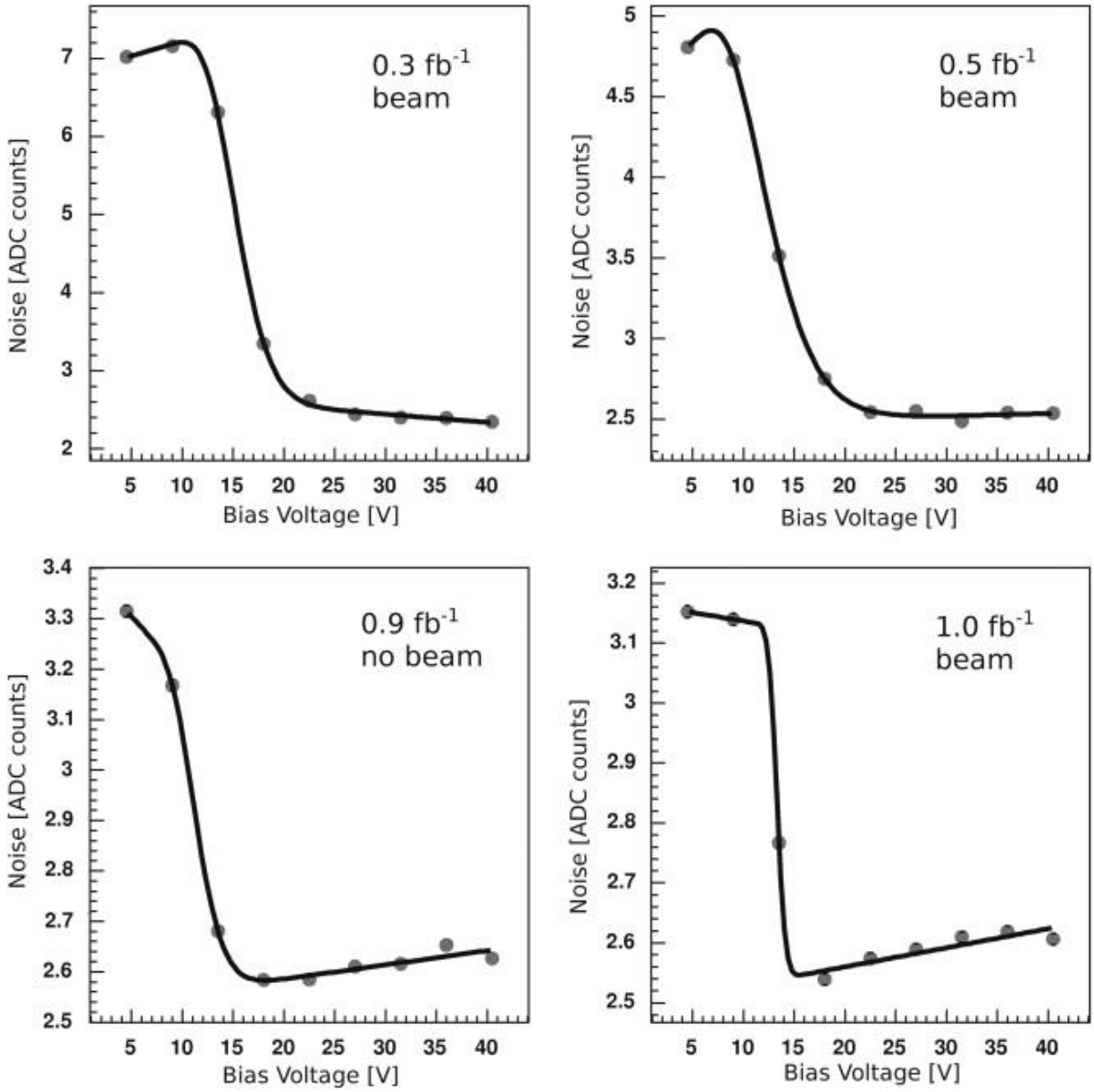
- “Silicon Detectors” Fermilab Academic Lectures *by Ron Lipton*
- “Making Tracks at D0” University of D0 lecture *by Satish Desai*
- References indicated in the above presentations

BACKUP SLIDES

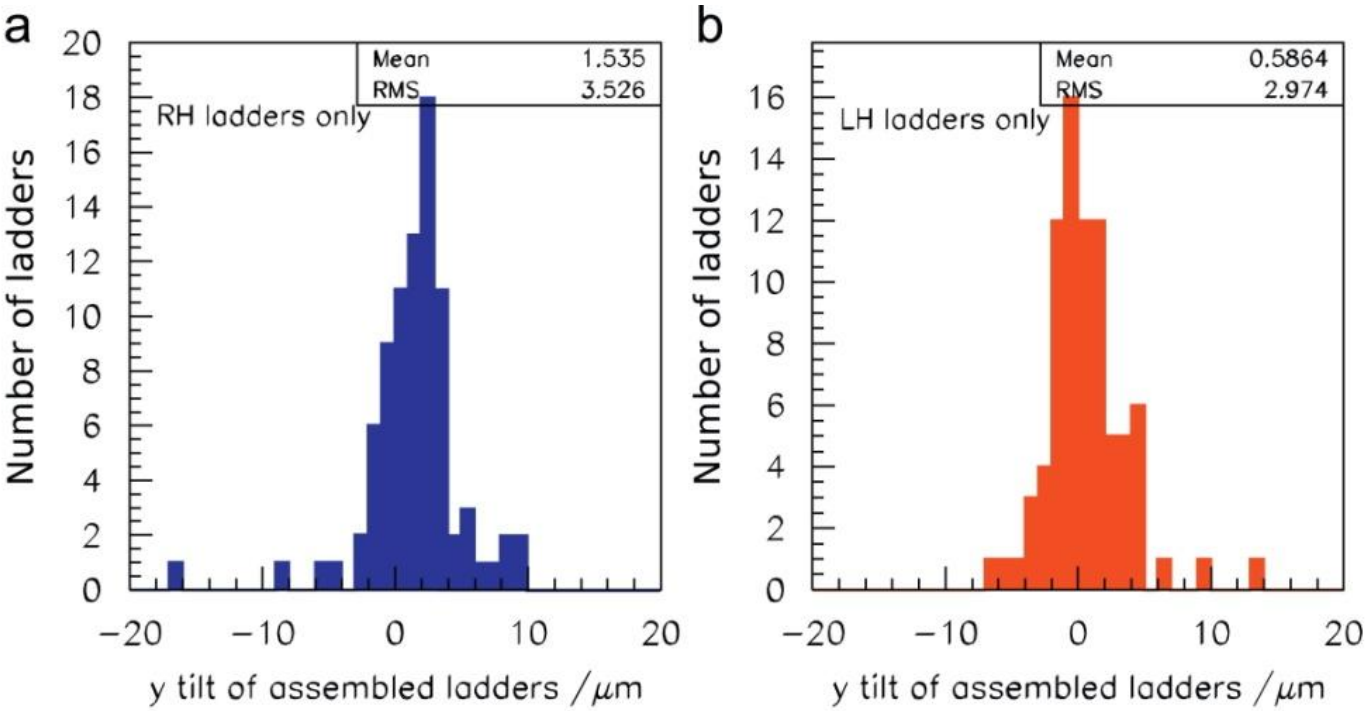
Depletion Voltage Measurement (before installation)



Depletion Voltage Measurement (during detector operation)



Optical Survey Results
(before installation)



Single wafer ladders

Quality Evaluation Procedure

- Measurement
  - ✓ establish coordinate system using leftmost middle and rightmost middle optical targets
  - ✓ measure optical targets, beryllium notches, and accessible surfaces

- Data processing
  - ✓ Rotate and translate from the measurement coordinate system to assumed nominal coordinate system (minimize $\sum_{\text{data points}}[(X_{data} - X_{nom.})^2 + (Y_{data} - Y_{nom.})^2]$)
    - ✓ within each sensor
      - ✓ check that the deviations are within 5 microns, otherwise discard > |5 microns| points and refit
    - ✓ repeat for the whole ladder
    - ✓ express beryllium measurements in the new coordinate system
    - ✓ check for deviations from nominal beryllium locations

Charge Drift

The local velocity of a charge carrier

$$v(x) = \mu E(x) = \mu E_0 (W - x)$$

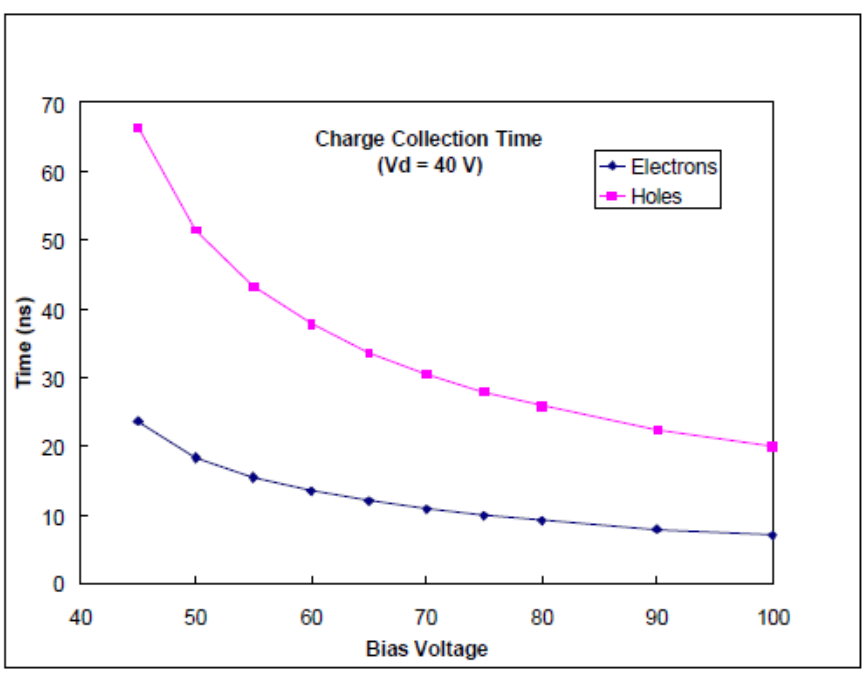
The time required for a charge originating at x_0 to reach a point x is

$$t(x) = \int_{x_0}^{x} \frac{1}{v(x)} dx = \frac{1}{\mu E_0} \int_{x_0}^{x} \frac{1}{W - x} dx = -\frac{1}{\mu E_0} [\ln(W - x)]_{x_0}^{x}$$

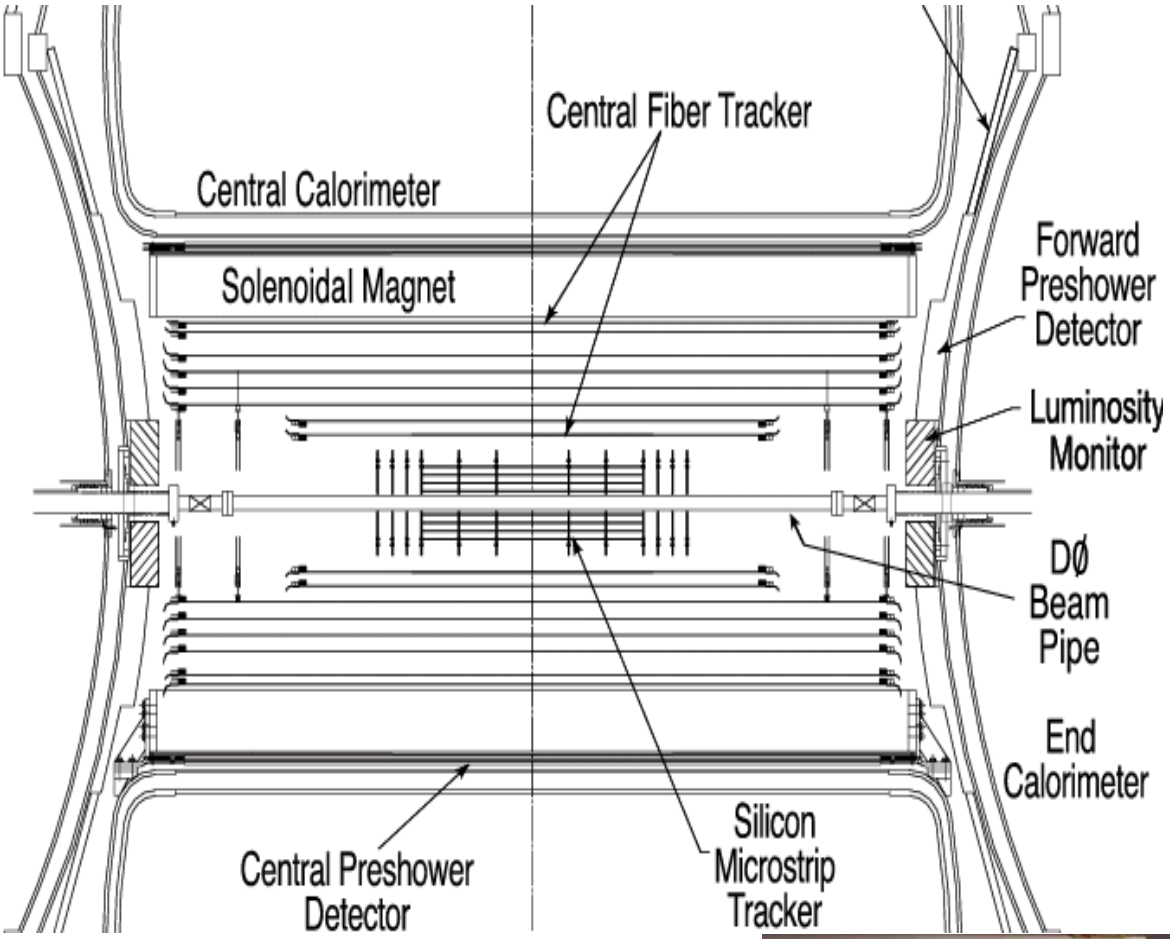
$$t(x) = -\frac{1}{\mu E_0} \ln \frac{W - x}{W - x_0} = \frac{\varepsilon}{\mu q_e N_d} \ln \frac{W - x}{W - x_0} \qquad (19)$$

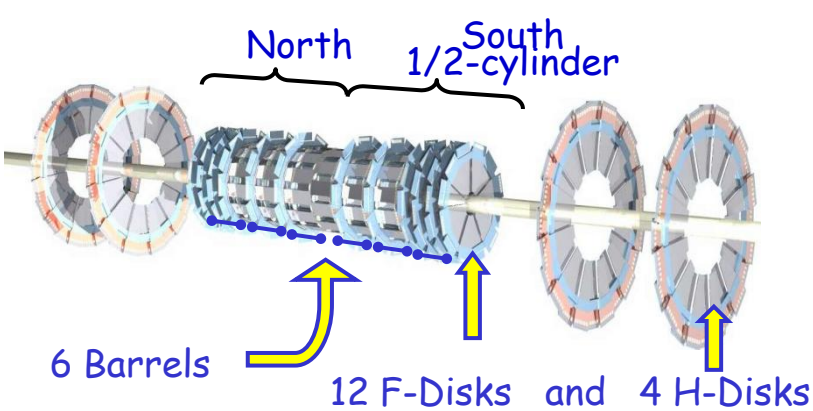
Consider a hole drifting toward the high-field region and collected at the p-electrode $x = 0$. Using the hole mobility μ_p eq. 19 yields

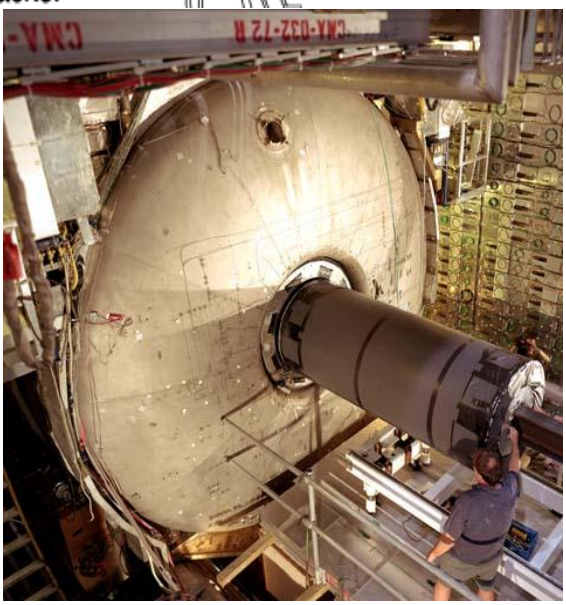
$$t(x_0) = -\frac{1}{\mu_p E_0} \ln \frac{W}{W - x_0} = \frac{\varepsilon}{\mu_p q_e N_d} \ln \frac{W}{W - x_0} \qquad (20)$$



More DØ Detector Pictures







Layer Ø Performance

8.2 Performance

The new detector has significantly improved the physics performance of the D0 detector. Since it was designed to improve the vertex resolution, it is not surprising that the biggest gain is in the measurement of the impact parameter. Figure 12 shows the impact parameter resolution with and without the Layer 0 detector.

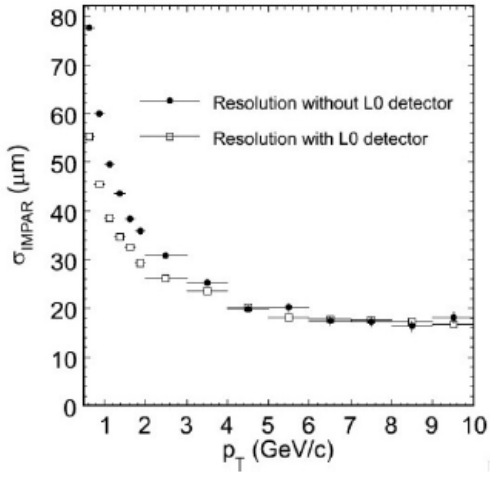


Figure 12. The impact parameter resolution with and without the Layer 0 detector.

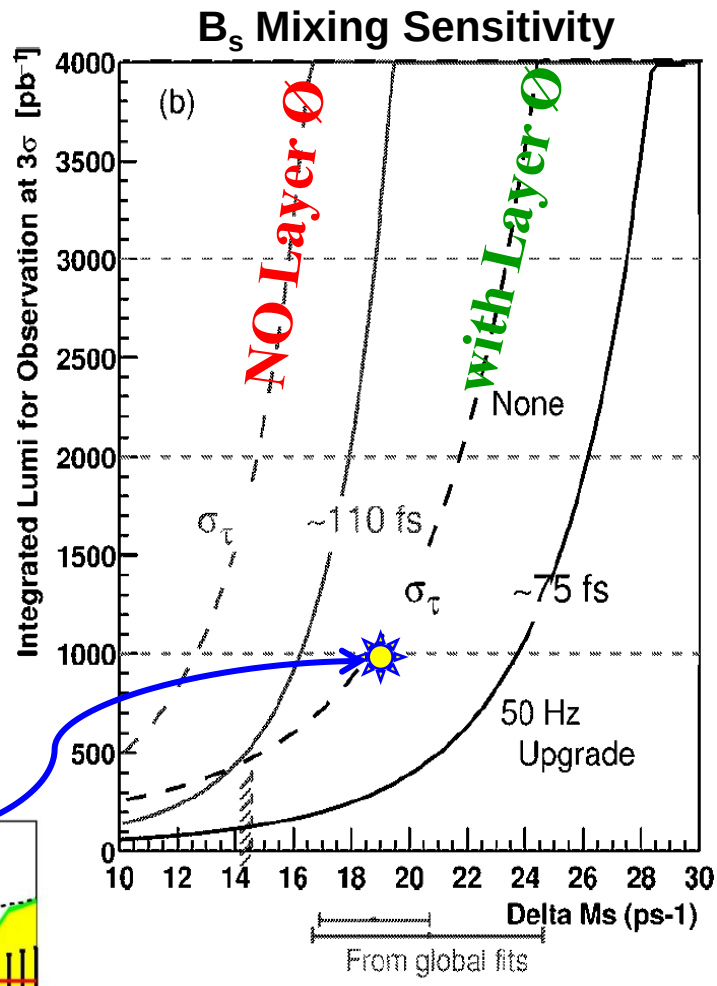
The distribution accounts for the L0 intrinsic resolution (strip pitch), position of first hit, multiple scattering and vertex position uncertainty. For P_T values less than about 2 GeV/c the improvement in resolution is greater than 20%

Layer Ø Impact on DØ Physics

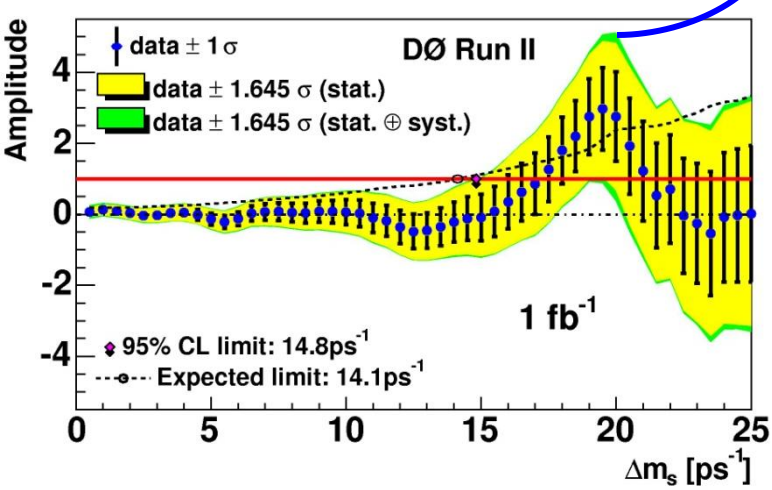
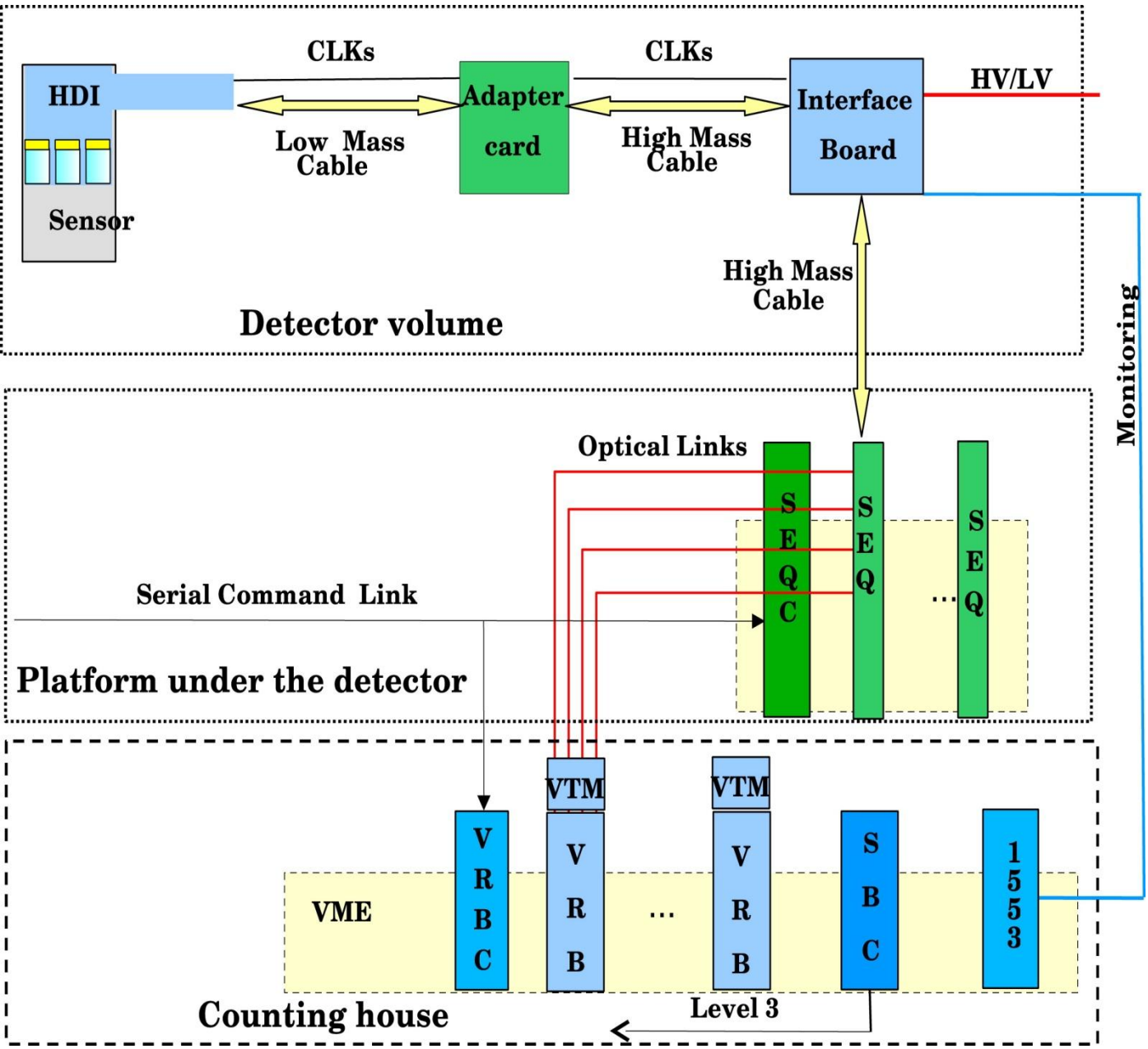
B_s Lifetime Resolution at DØ:

110 fs without Layer Ø

75 fs with Layer Ø



DØ PRL of 2006



DØ SMT Readout System