

# **SEMICONDUCTOR MICROPATTERN PIXEL DETECTORS : A REVIEW OF THE BEGINNINGS**

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**Overview**

**Historical**

**Monolithic and Hybrid**

**Essential aspects of pixel detectors**

**Segmentation allows low noise, with several trade-offs**

**Pixel detectors have been developed in RD19  
and have already been applied in 3 experiments**

**Heavy ion experiment WA97/NA57**

**NA50 high intensity heavy ion experiment**

**DELPHI Very Forward Tracker at LEP collider**

**Conclusion : Pixel detectors, dream or nightmare ?**

# Pixel Detectors : Beginnings

**A natural step based on existing technology:**

## Semiconductor Nuclear Detectors

Single diode spectrometer	1952
Segmented diode array checker board	1964
Position-sensitive diode with resistive layer uses ion-implantation	~1975
MOS, clean ion implantation	1980

## Nuclear Signal Processing Circuits

Discrete, Hybrid, Integrated Full Custom

## Semiconductor Imagers (monolithic)

BBD, CCD  
CMOS imagers

## Flip-Chip Technology

Computer modules IBM ~ 1964  
IR imagers  
Multi Chip Module integration

---- > **2 - D Particle 'Imagers'**

# Semiconductor Imagers

**BBD and CCD first developed ~ 1968 - 70**

Visible imaging Philips, Bell-Labs, RCA,..

BBD uses transistor array

CCD uses MOS capacitor array

CCD are monolithic, output amplifier integrated

High voltages : 10-20 V, special technology

Also : analog memory and signal processing

**CCD and Direct Read Out for IR sensors**

Military & Space imaging Hughes, Rockwell,..

-- Monolithic eg. Pt on Si used at 4 K

-- Connect chips to different sensor materials  
CdHgTe with tailored bandgap

**CMOS imagers begin ~ 1990**

Visible imaging geometric fill factor

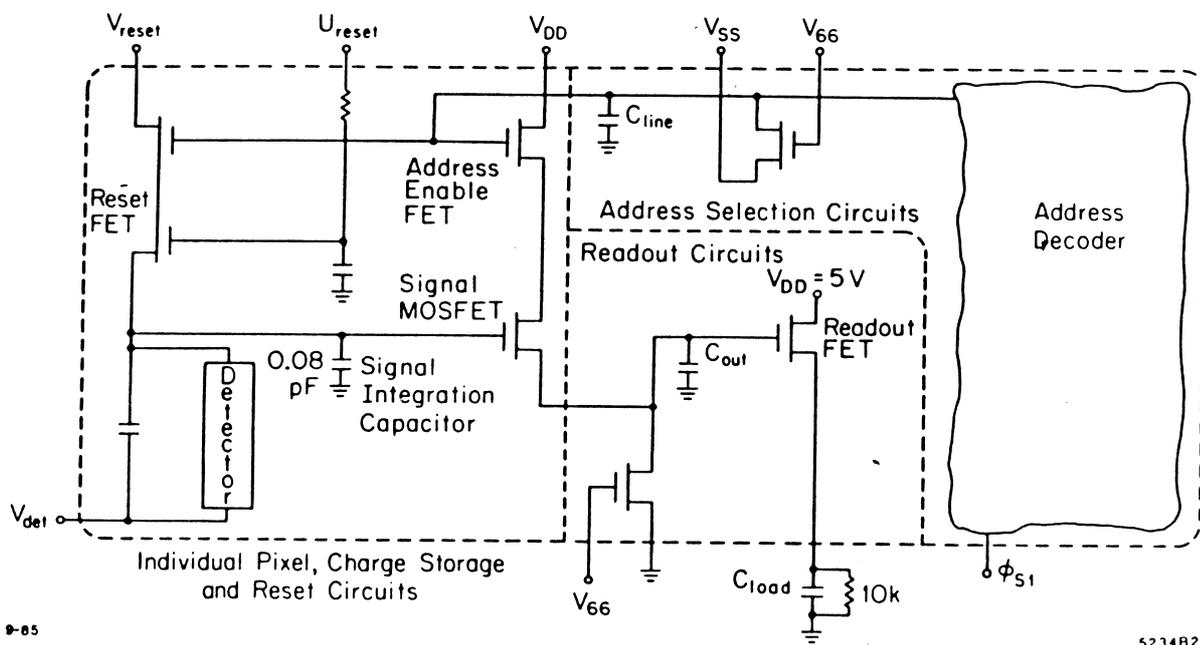
Integrated signal processing, ADC, ...

# Early Pixel Readout

## Charge Integration with Random Access

Gaalema (Hughes) 1984 IEEE NSS  
transistor pixel cell

3



Identical circuit for SSC test chip 10 x 64  
Shapiro/ Gaalema Leuven 1988

256 x 256 NMOS and PMOS arrays  
used in test beam at Fermilab August 1990

# Pixel Detectors : First Steps

## Ideas ('invisible') from 197x

Shapiro SLD rep 1984    Heijne SPIE 591, 1985

## CCD applied in NA32 and SLD

Damerell since ~1981

## Imager papers NSS 1984

Gaalema (Hughes, Carlsbad)    random acces

Blouke (TI), Janesick cs (JPL) 10  $\mu\text{m}$  CCD

## Hughes / SLAC / LBL (Shapiro, Nygren, cs)

SSC development contract ~ 1990

based on hybrid IR imagers for space & astronomy

## Monolithic pixel development

Parker, Kenney, Snoeys / Stanford for SSC

development in CIS ~ 1989 - 1992

Vanstraelen, Dierickx, Pengg, Heijne / IMEC

bulk Si, SOI    1986 - 1995

MPI Munich    drift, DEPMOS

## Initiatives at CERN (Heijne, Jarron, cs)

Pixel development in LAA 1986 - 1989

'Pixel-Dream' paper London 1987

Consult E. Vittoz CSEM/EPFL + ETHZ

1st readout chip LAA 9 x12 1988

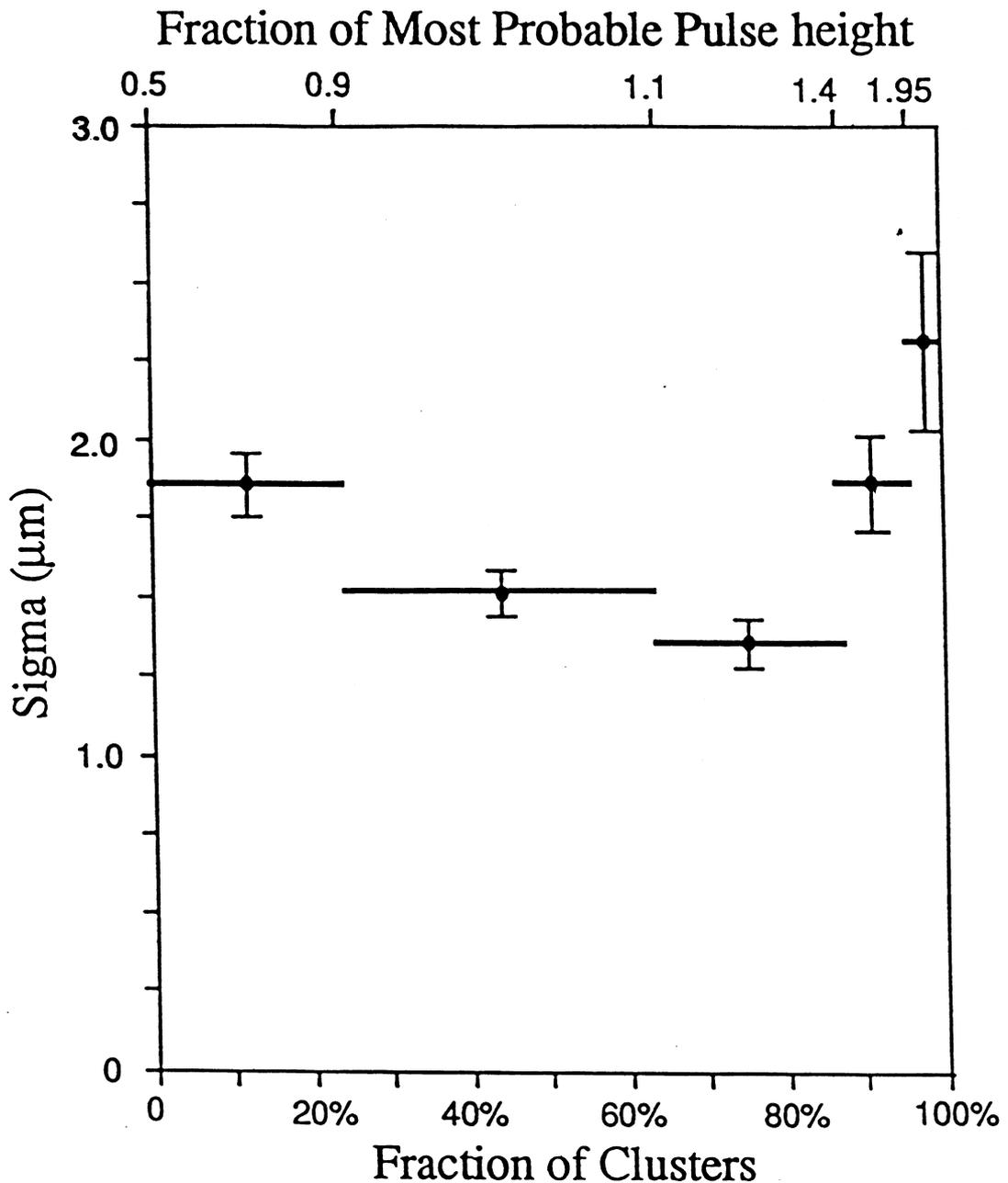
Pixel Workshops Leuven 1988 1990

RD19 involving several institutes 1990

# Monolithic Analog Pixel Matrix

## SLAC :Parker, Kenney, Snoeys

Fermilab muon beam test  
Small input capacitance in monolithic



Precision close to 1 µm for 34 µm pitch  
Large signals ( -ray) 'worse' precision

# **HYBRID VS Monolithic Pixel Detectors**

## **Developments in MONOLITHIC :**

**CCD          RAL          Damerell**

**SLAC/Stanford    Parker**

**IMEC                          Vanstraelen, Dierickx**

**MPI/Munich    based on drift and DEPMOS**

**Monolithic has appeal of elegance**

**Lowest noise allows sensing layer ~ 20  $\mu\text{m}$**

**3-D technology improves monolithic future**

**Could be cheap if it uses mainstream CMOS**

## **HYBRID**

**Hybrid approach has more flexibility**

**Common development for different sensors**

**Building block in array can be larger**

**nearly wafer-size sensor / substra**

**MCM technology improves hybrid future**

# Pixel Detectors : Principles

**Microscopic Segmentation -->  $10^4 \text{ cm}^{-2}$**

System with  $10^8$  distinct sensor elements

Need for on-chip signal processing

and information extraction

**Integrate Signal Processing in / near pixel**

Replace Passive Charge Integrator

Classic Nuclear Chain

Monolithic Chip

Hybrid Assembly

**Small Sensor/ Ampli Capacitance ~ 100 fF**

Low noise ~  $100 \text{ e}^- \text{ rms}$

Reduced Power <  $0.5 \text{ W cm}^{-2}$

**Variety of trade-offs :**

CMOS used instead of FET or bipolar

Alternative approach to Radhard

Differen

sensors possible: Epitaxial  $\sim 60\mu\text{m}$

**After all : Orders of magnitude difference**

**Radical Change**

# **Micropattern Pixel Detectors**

## **New and Needed**

**Starting point : Use only / adapt to commercially available technology**

**The real innovation is miniaturization of complete nuclear pulse processor in pixel**

**Shortest connections for low capacity/noise**

**Readout on sensors, how to take heat out ?**

**Low noise is fine, but in binary system threshold dispersion must be same order**

**Comparator is always needed to give input for selection logic that labels good data**

**Analog signal content useful in some cases**

**Foresee trends in microelectronics  
(eg. deep submicron for radhard )**

**Pixels+powerful computers crucial in getting physics from the too many LHC events**

## **Noise in Pixel Cells**

**Noise is so low that it is no issue by itself**

**Understanding and improvement of noise important to allow various trade-offs**

**Different optimization may be found for signal/noise/speed/power**

**Noise measurements need to be done on absolute scale, use  $\gamma$  source**

**Understanding of components capacity at input amplifier still incomplete**

**Operational 'noise' may be dominated by digital crosstalk, power supply, beamRF**

**Variance on comparator threshold setting must match noise  
active compensation needed**

# **Pixel Detectors**

## **First Beam Tests and Experiments**

**SLAC / LBL Space / Hughes Carlsbad**  
Charge Integration IR chip  
1 matrix 256 x 256 in 250 GeV  
August 1990 at Fermilab

**RD19 / Omega - D binary + periphery**  
3 detectors 16 x 63 cells of 500 x 75  $\mu\text{m}$   
parasitic WA 94 heavy-ion summer 1991  
beam tracks  
reconstruction vertex in target

**Stanford monolithic matrix, analog+drivers**  
4 detectors 10 x 30 cells of 125 x 34  $\mu\text{m}$   
muon beam tracks Fermilab autumn 1991

**Omega2 array 36kpix in PS beam sept1993**

**Omega2 Omega3/LHC1 planes WA97/NA57**  
72 kpix in Nov 1993  
300 kpix Sept-Dec 1994

**DELPHI VFT first collider application 1994**  
5/8 installed : 613 kpix

# Comparison of Pixel Detectors in experiments

(chips based on RD19 developments)

	<b>WA97/ NA57</b>	<b>DELPHI</b>	<b>NA50/ NA6i</b>
<b>since</b>	<b>1994/5</b>	<b>1996/7</b>	<b>1997/8</b>
<b>until</b>	<b>200i ?</b>	<b>2000</b>	<b>200i ?</b>
<b># kpix</b>	<b>1093</b>	<b>1226</b>	<b>67 / 790</b>
<b>area</b>	<b>372</b>	<b>1335</b>	<b>test 18</b>
<b>cm<sup>2</sup></b>			<b>200</b>
<b># chips</b>	<b>792</b>	<b>2432</b>	<b>~200</b>
<b># wafers</b>	<b>~ 80</b>		

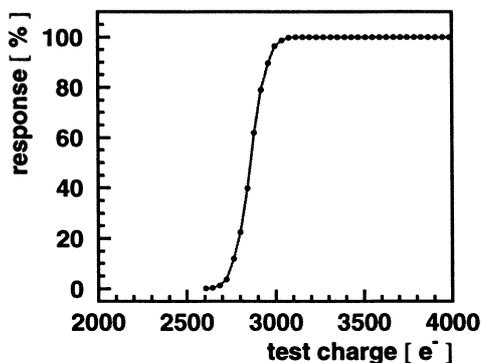
# Readout chip Omega3/LHC1

## Threshold settings and Noise

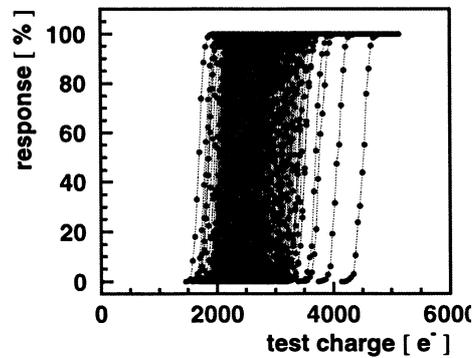
Each pixel cell has analog test input

Effective noise of amplifier-comparator can be determined from slope of response curve

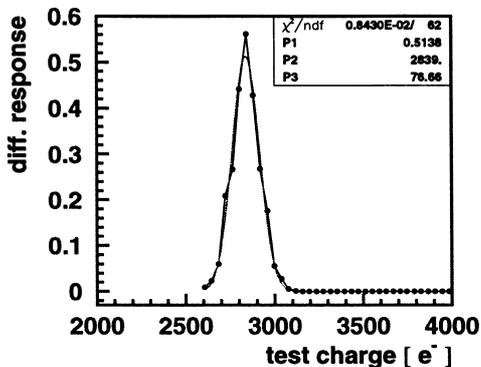
After absolute calibration the noise distribution can be made



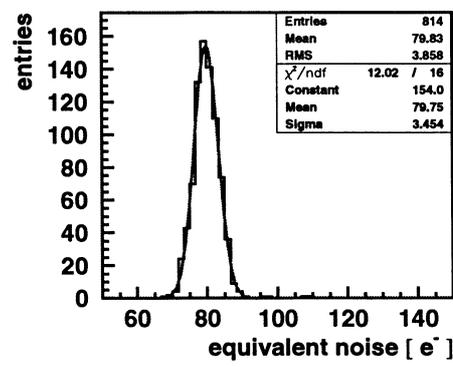
(a.)



(c.)



(b.)



(d.)

noise value unbonded chip  $80 \pm 4 e^-$  rms

idem bonded chip  $160 \pm 12 e^-$  rms

absolute calibration bonded  $\sim 220 \pm 30 e^-$  rms

# Readout chip Omega3/LHC1

## Threshold settings

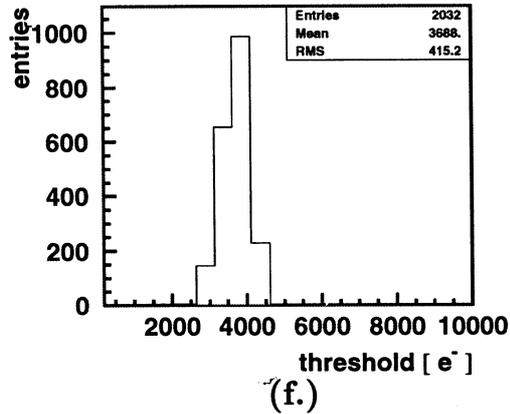
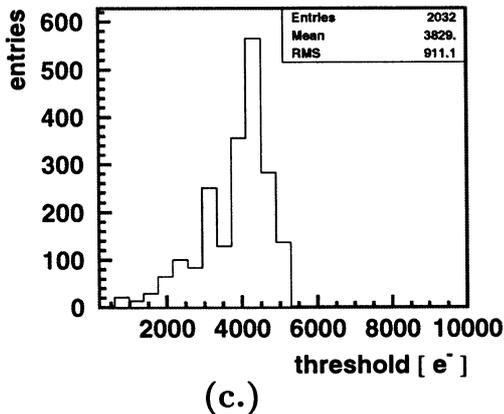
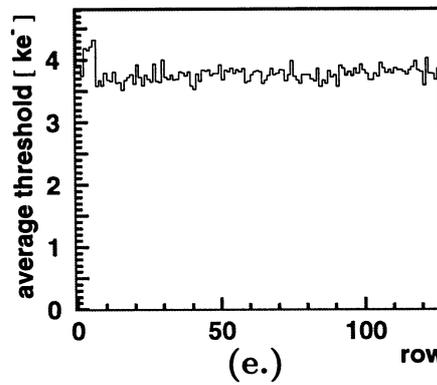
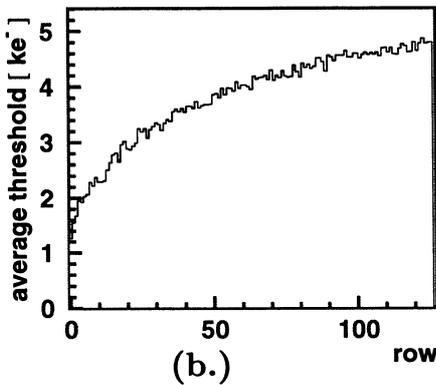
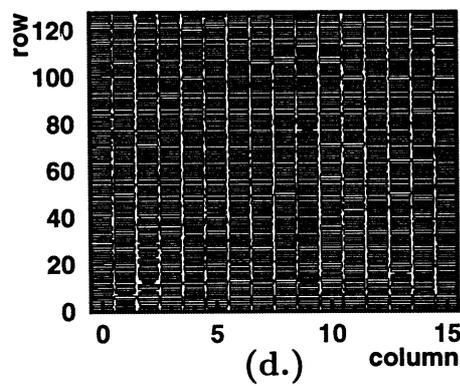
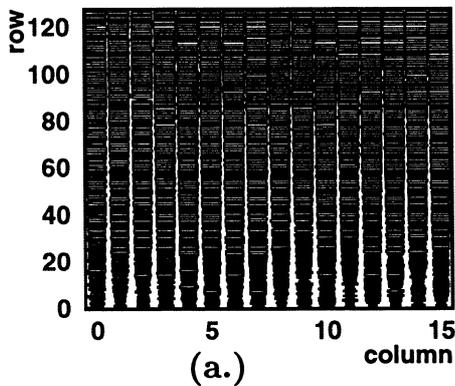
Uniformity can be compromised if power distribution is inadequate

LHC1

900 e<sup>-</sup> rms

LHC1'

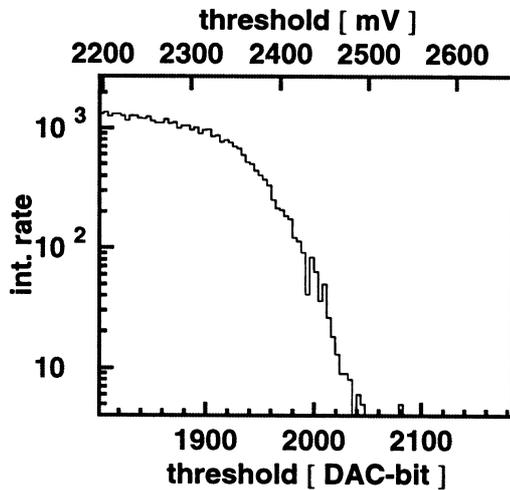
400 e<sup>-</sup> rms



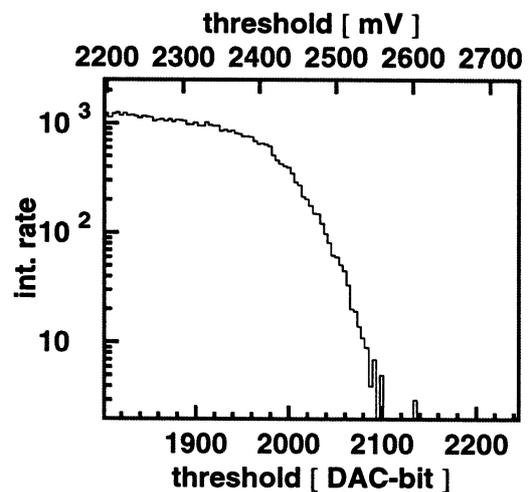
# Readout chip Omega3/LHC1

## Comparison type C and type A sensors

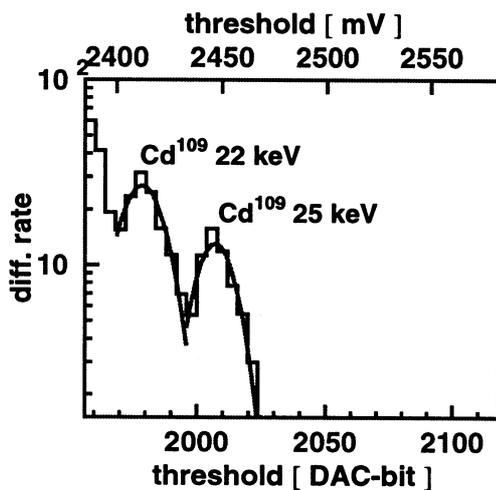
### Calibration with $^{109}\text{Cd}$ source



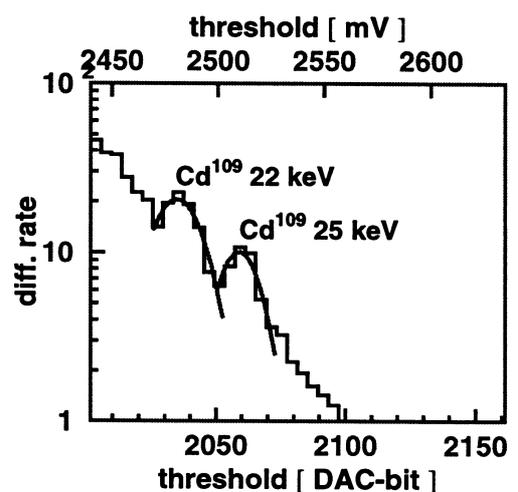
(a.)



(c.)



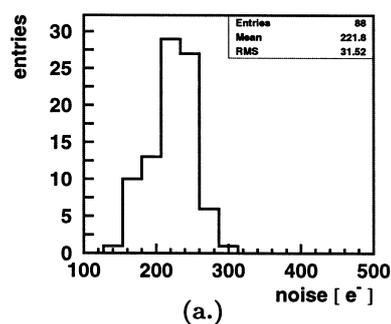
(b.)



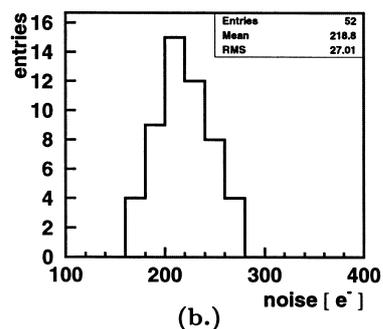
(d.)

Noise for 44 C) cells  $222 \pm 32 e^-$  rms (1.89 keV)

Noise for 26 A) cells  $219 \pm 27 e^-$  rms (1.86 keV)



(a.)



(b.)

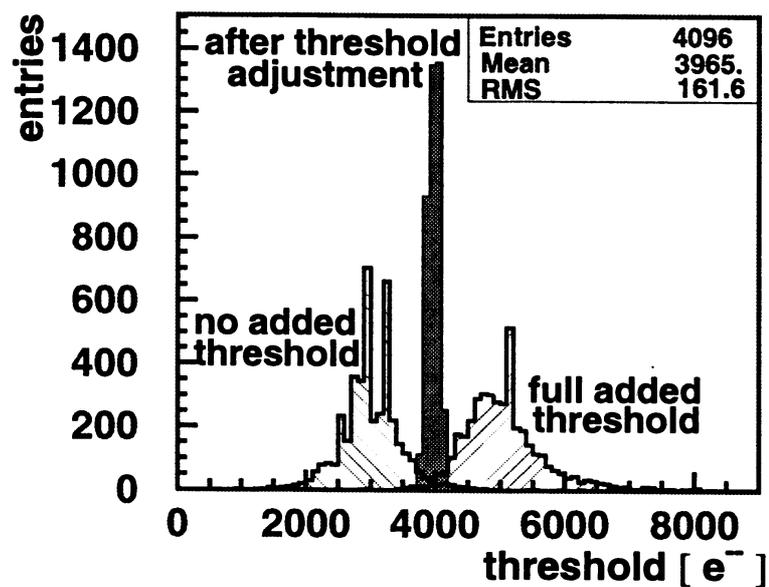
# LHC1 / PCC Threshold Adjust

3 - bit binary trimming of thresholds improves threshold distribution

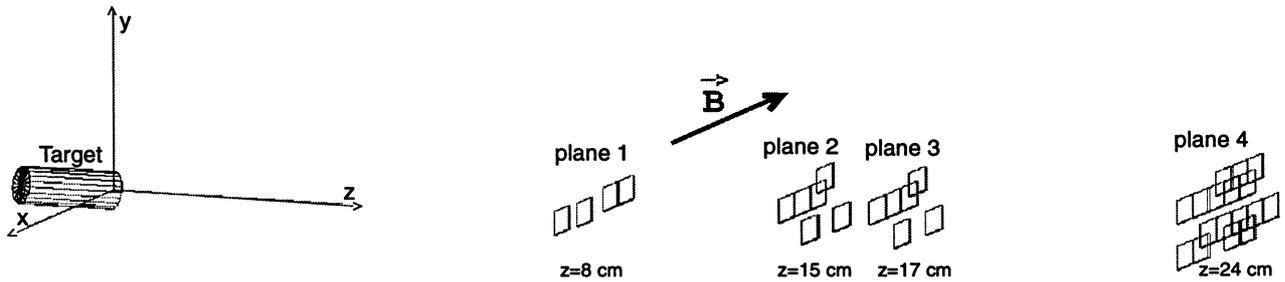
3000  $e^- \pm 450 e^-$  rms no added threshold

5000  $e^- \pm 700 e^-$  rms full added threshold

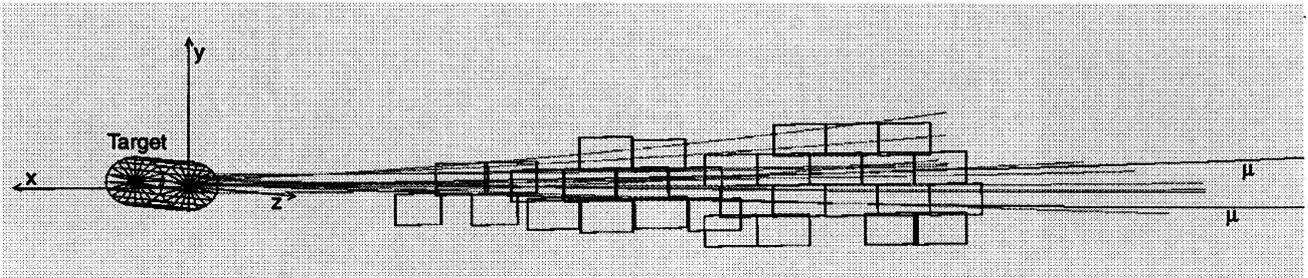
4000  $e^- \pm 160 e^-$  rms trimmed threshold



# NA50 Test 1998



NA50 has 5.4 m long hadron absorber  
 Pixel telescope used as vertex detector  
 for muon tracking near the target

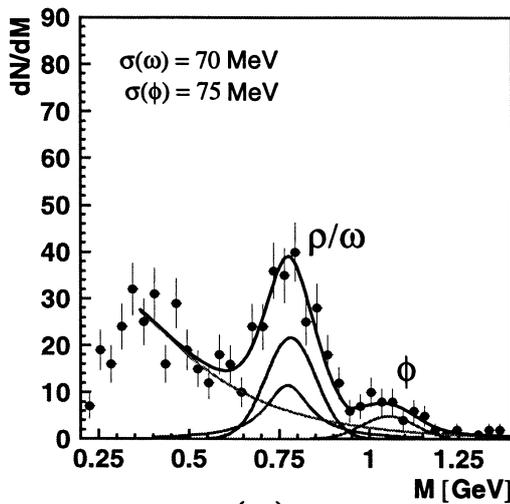


Event display with matched muon pair

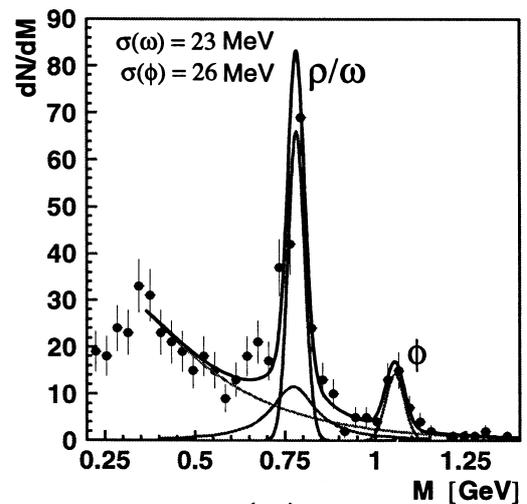
Dimuon Spectrum :

NA50 old

with pixels



(a.)



(b.)

# Radiation Test LHC1 in NA50

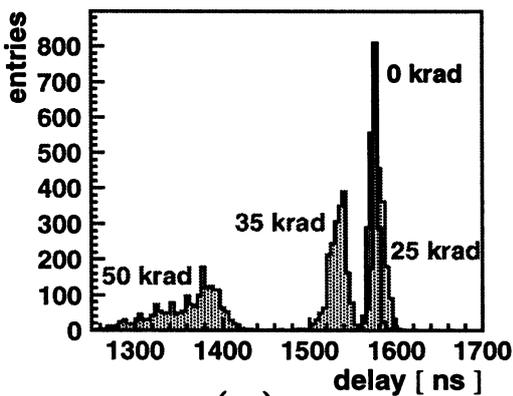
NA50 is high rate, high intensity experiment  
Pixel telescope was placed close to target

Chips are not radhard, made in 1  $\mu\text{m}$  SACMOS

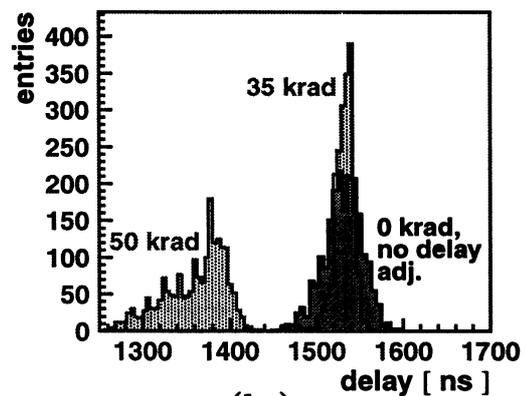
Failure mechanisms related to threshold shifts

Failures in beam reproduced with 10 keV X-rays

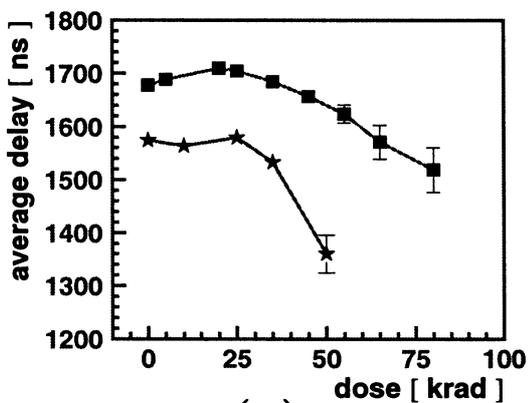
Chips trimmed at 0 krad    not trimmed  
<--- delay shortens



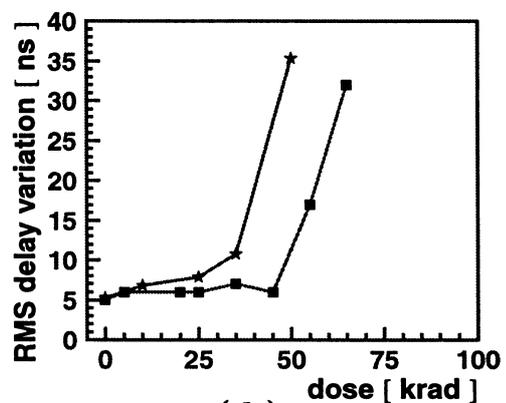
(a.)



(b.)



(c.)



(d.)

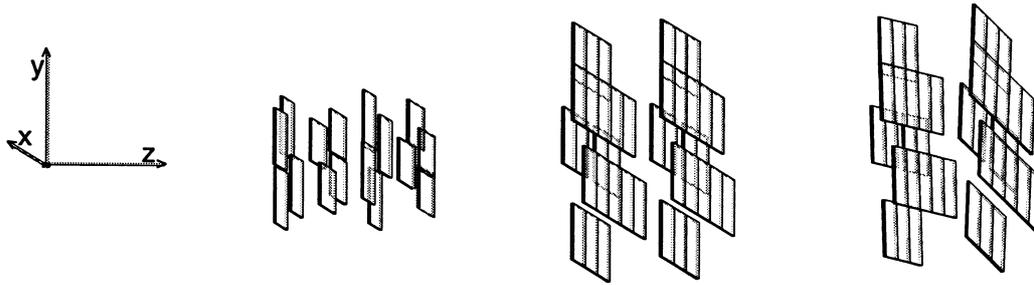
Average delay

Variance rms

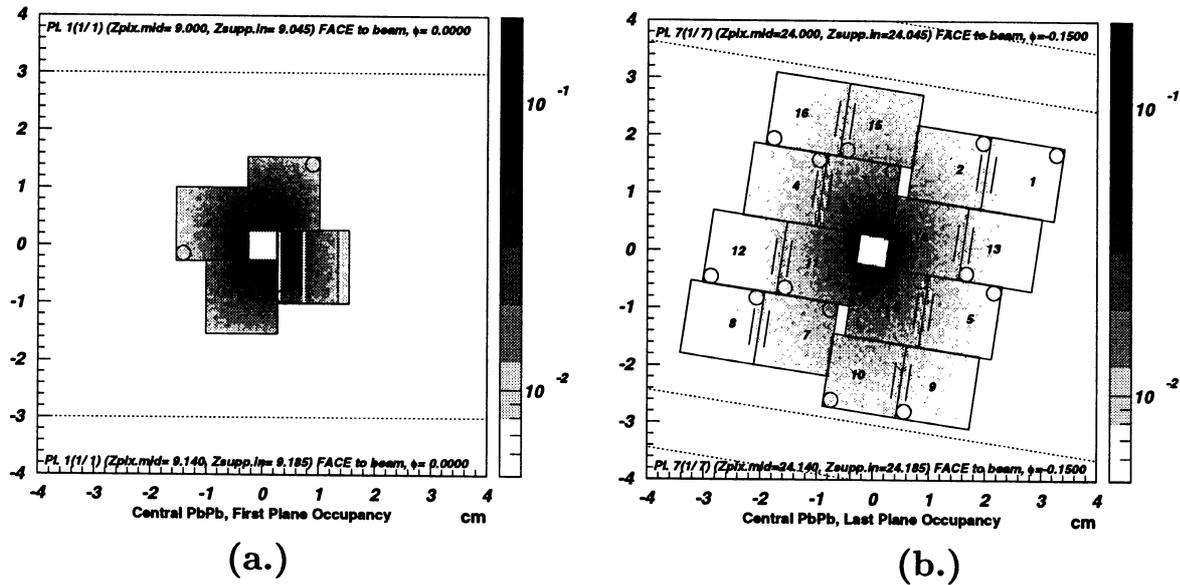
**Some recovery after anneal**

# NA6i Proposal for Vertexing in Pb-Pb

New pixel telescope around beam



Based on new ALICE1 readout chip



Simulation of hits in 2 planes

# DELPHI VFT pixel system

2 different chip sizes 24 x 24 and 16 x 24

152 substrate modules with 10 + 6 chips  
8064 sensor cells of 330 x 330  $\mu\text{m}$

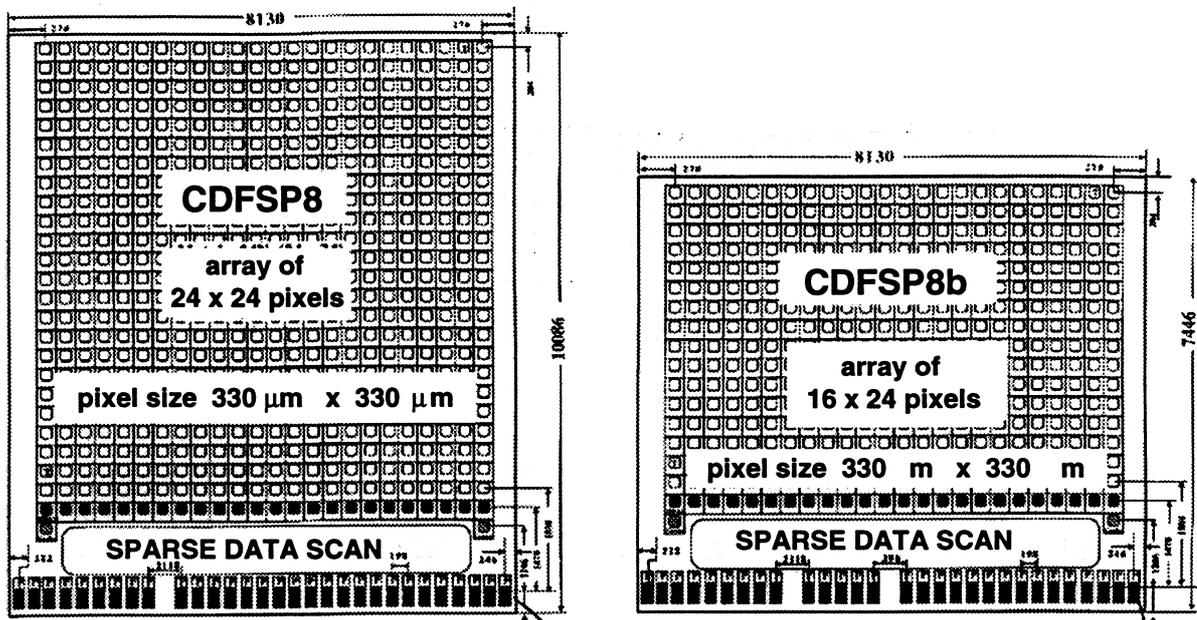
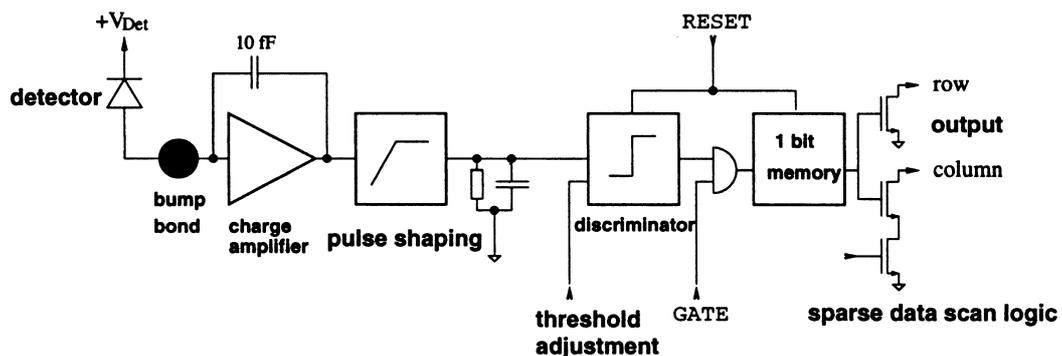


Figure 5.1: Layout of the readout chips CDFSP8/8b.



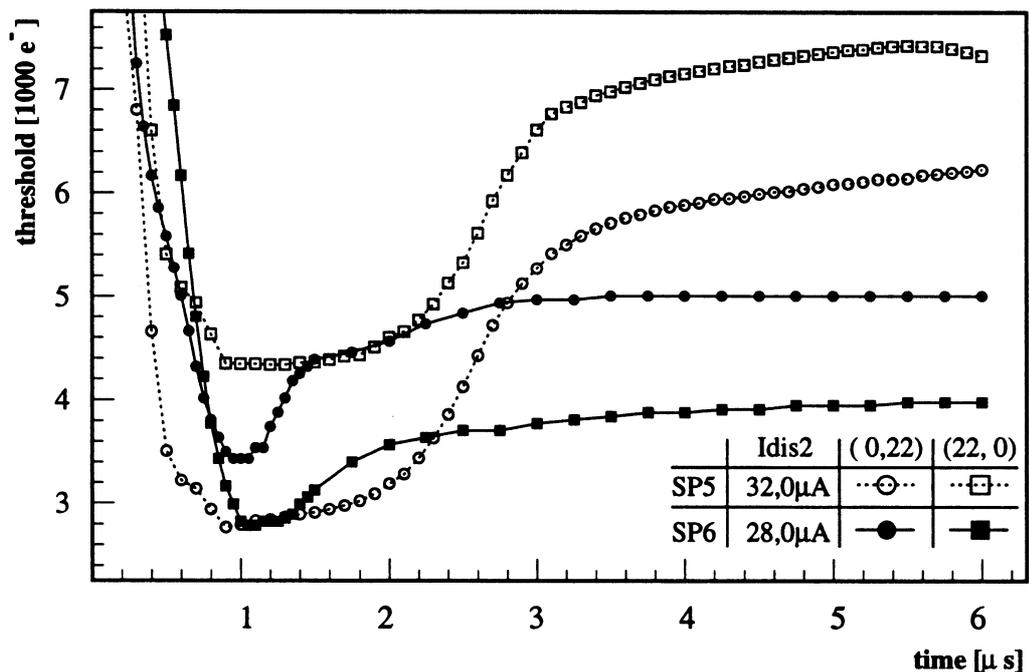
# DELPHI VFT pixel detector

Binary information, adjustable threshold  
has sparse readout, 0 suppression

Mati

Only 2 pixels have analog test input,  
and have different thresholds

Pixel cells have no hardware mask



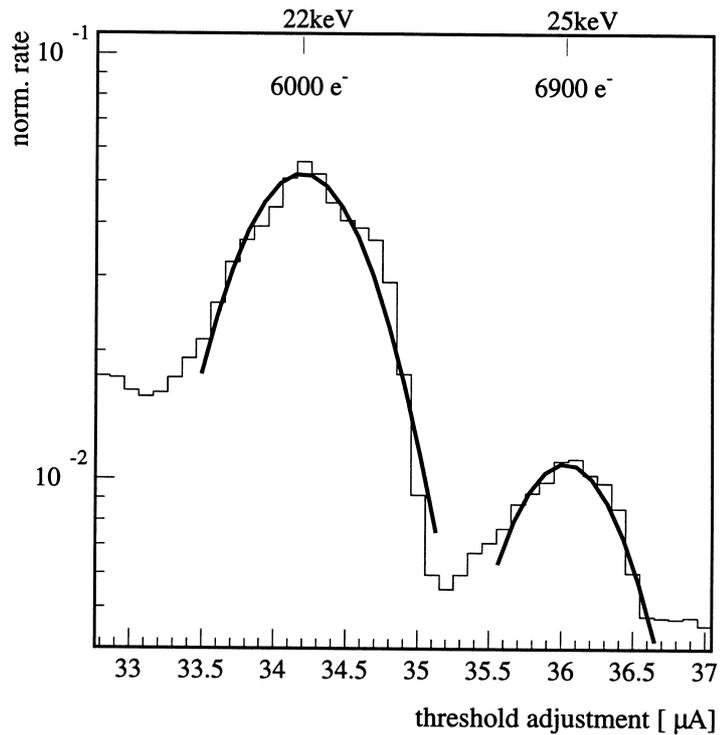
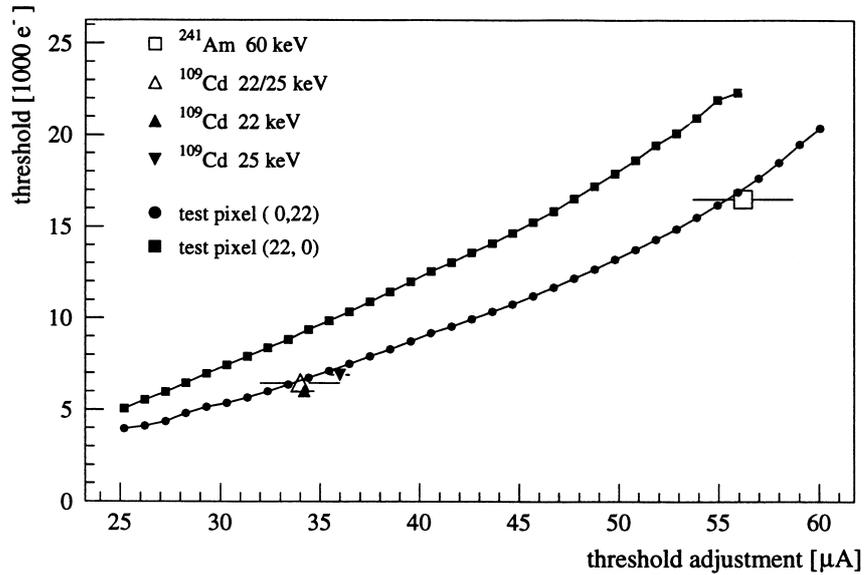
Threshold value varies after reset  
Minimum after  $\sim 1 \mu\text{s}$

Practical threshold  $\sim 8000 e^-$   
with variance  $1200 e^- \text{ rms}$

Elaborate procedures implemented  
to keep track on-line of noisy pixels

# DELPHI CDFSP6 Noise and Calibration

## Threshold curve using charge pulse injection



Absolute calibration of threshold with  $^{109}\text{Cd}$

Noise 230  $e^-$  rms

# DELPHI VFT pixel system

5/8 of VFT operational in 1996

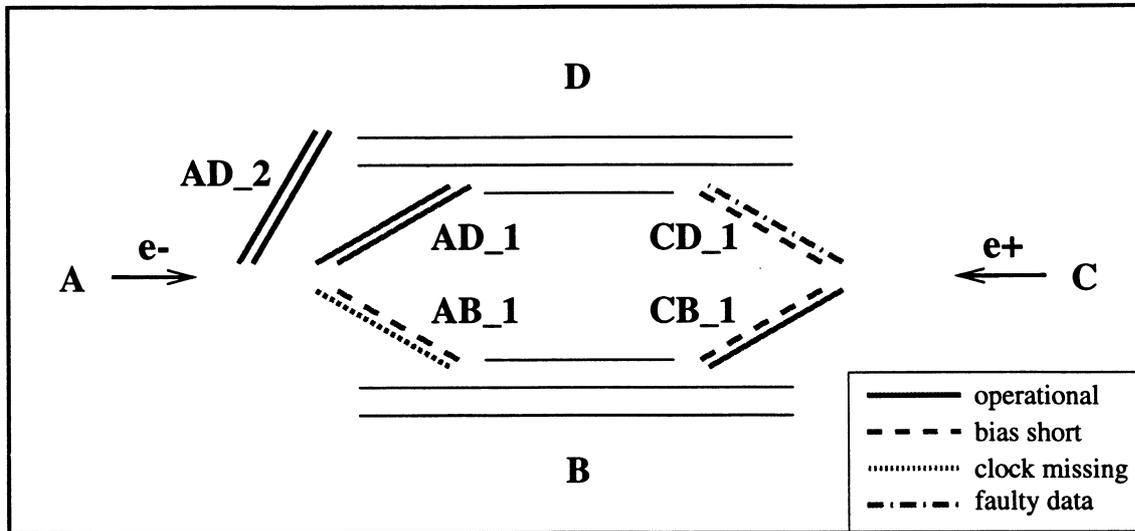
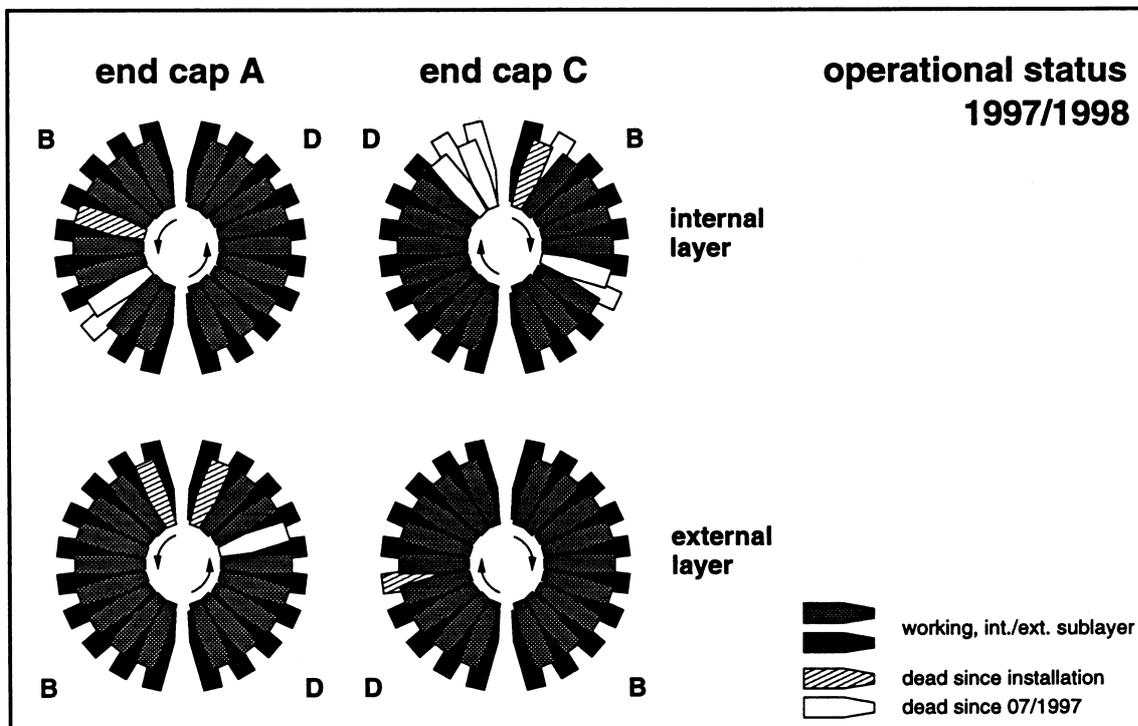


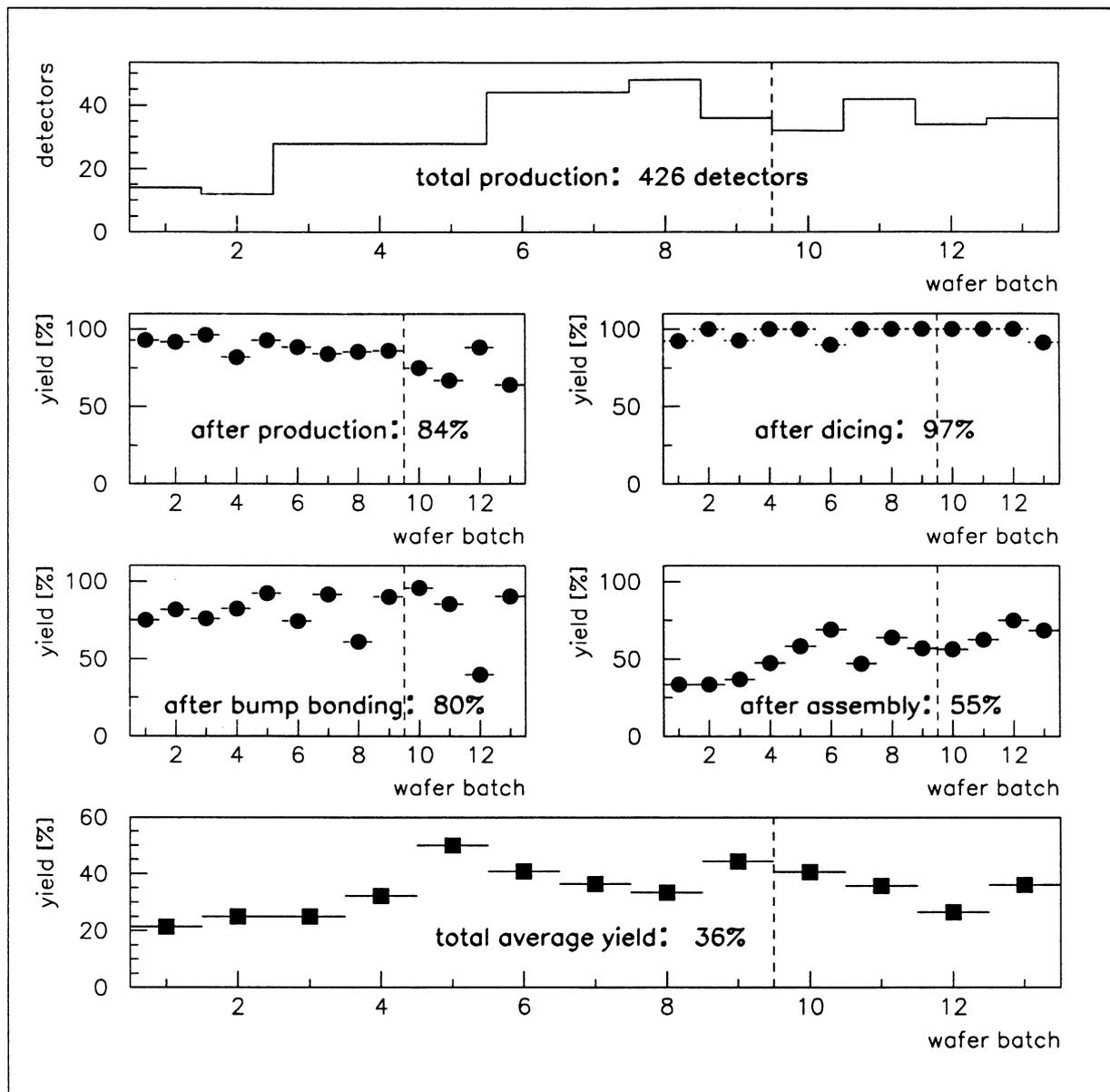
Figure 6.5: Operational state 1996.



Spring 1997 to end 2000      no interventions  
 152 modules, 5 + 10 dead      90 % OK

# DELPHI Production History & Yield

Detector substrates      426 --> 152    36 %



16 chips per substrate      168 per wafer

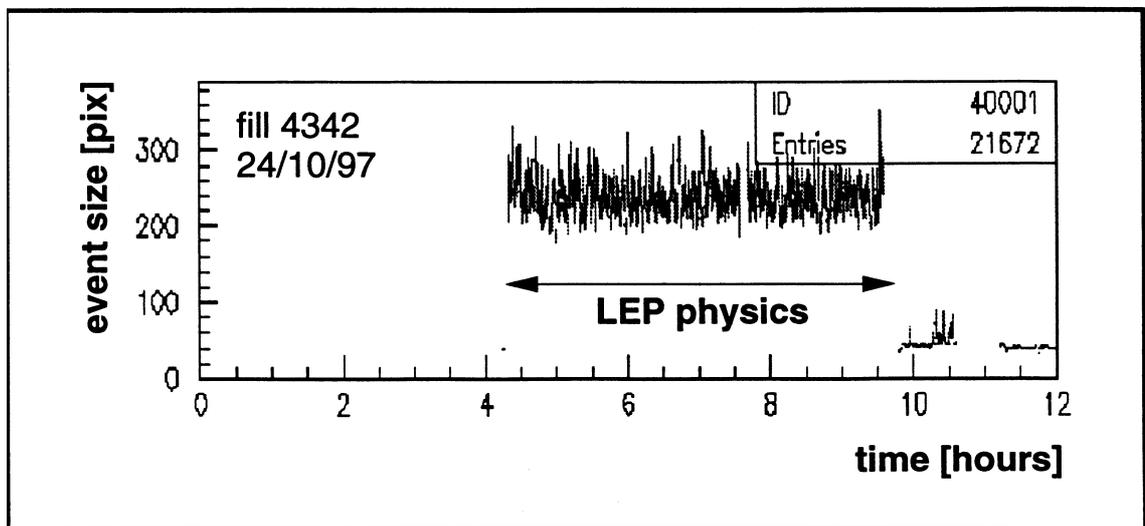
Yield of readout chips CDFSP8 ~ 65 %

# DELPHI VFT pixel system

## Occupancy of pixel modules

**Normal operation : 200-300 hits / event**

only a couple of real tracks,  
many 'spurious' photons or other 'junk'



How could this be in LHC ?? Even more 'photons'

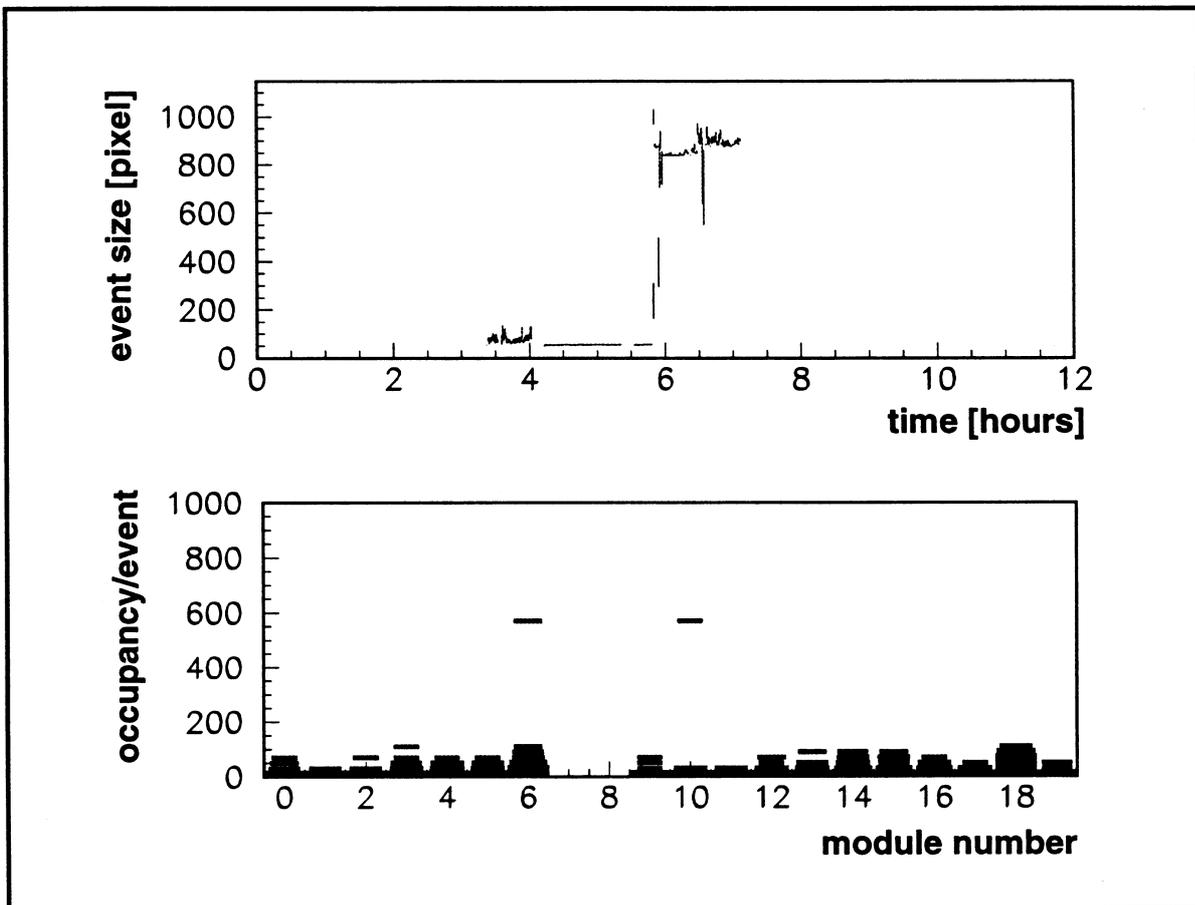
# DELPHI VFT pixel system

## Occupancy of modules in abnormal conditions

### Particle halo during injection

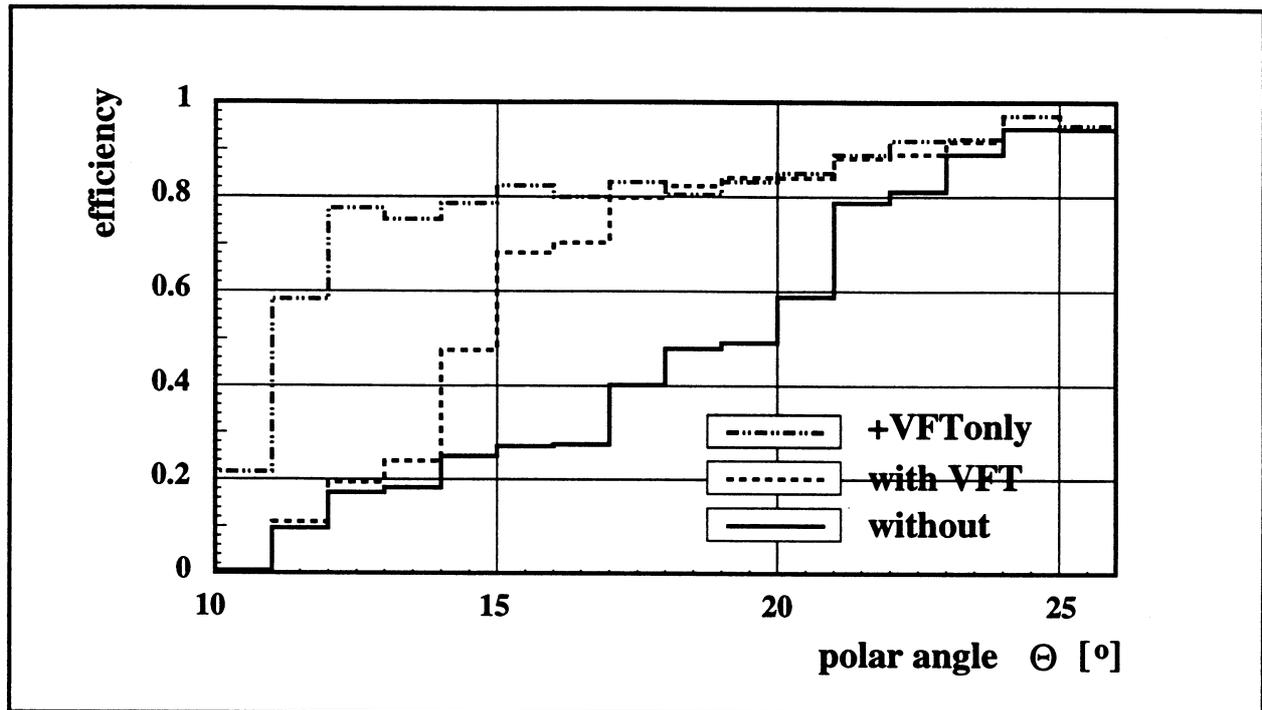
can lead to (temporarily) noisy module

threshold can be increased during injection



# DELPHI VFT pixel system Results

## Efficiency in tracking improved



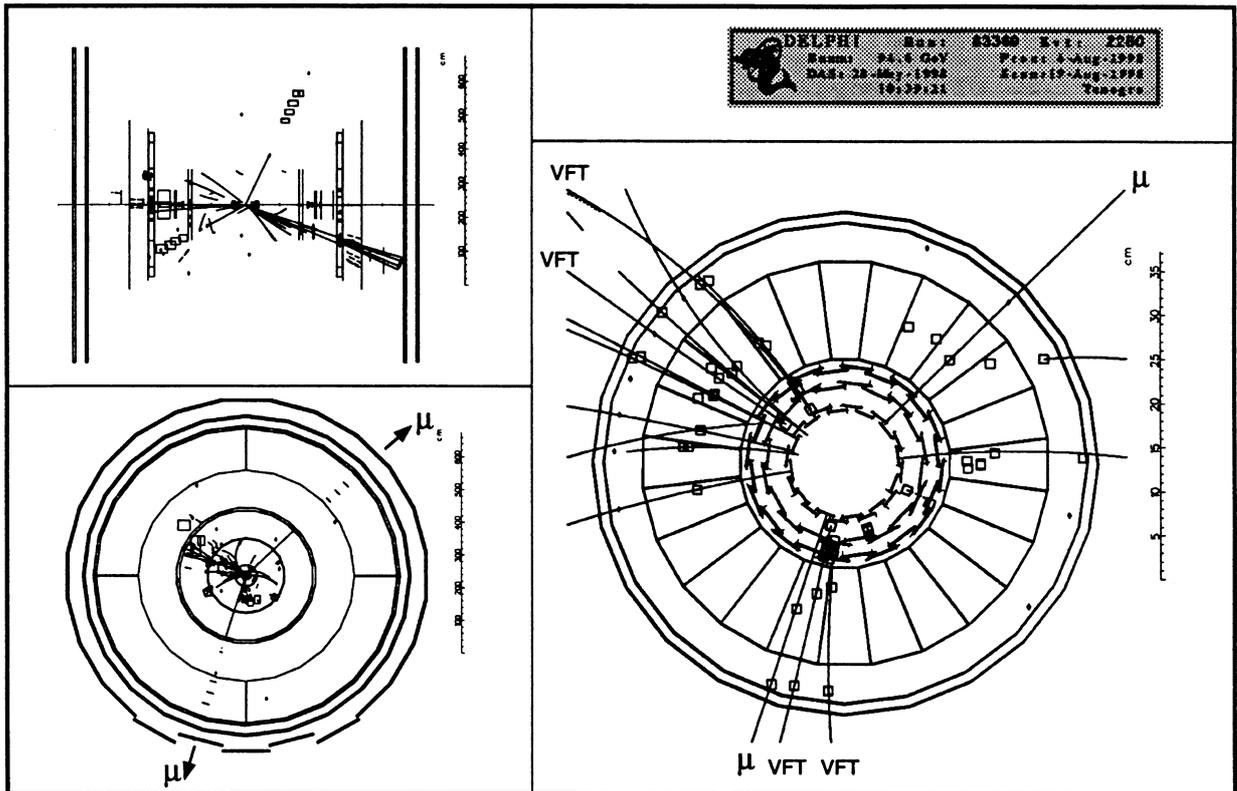
Stand-alone tracking is possible

Better coverage of forward region

Excess of photons : microstrips hard to use

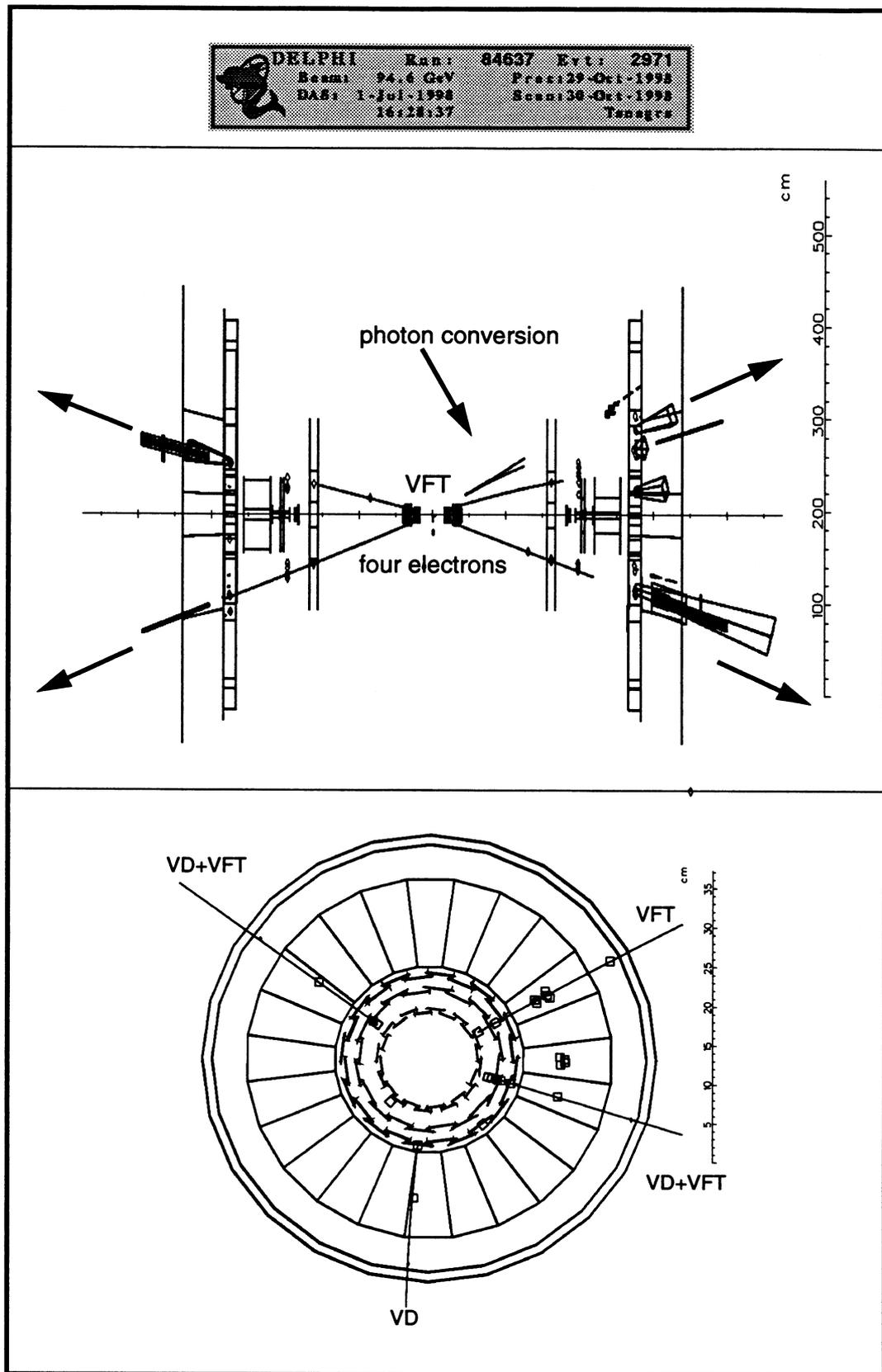
# DELPHI Pixel Detector Event Display

Shows very forward tracks in vertex region



$s = 189 \text{ GeV}$      $e^+e^- \rightarrow ZZ \text{ or } HH$   
VFT tracks are marked

# DELPHI Pixel Detector Event Display

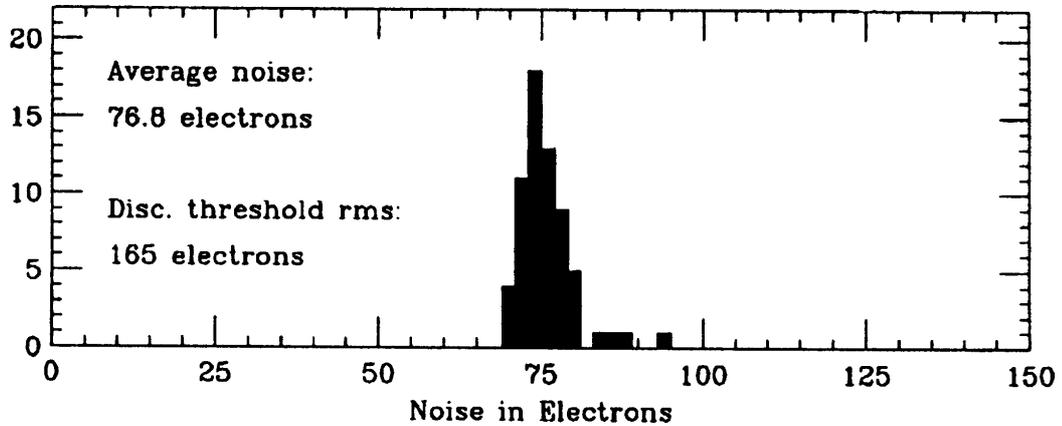


$$s = 189 \text{ GeV} \quad e^+e^- \rightarrow e^+e^-e^+e^-$$

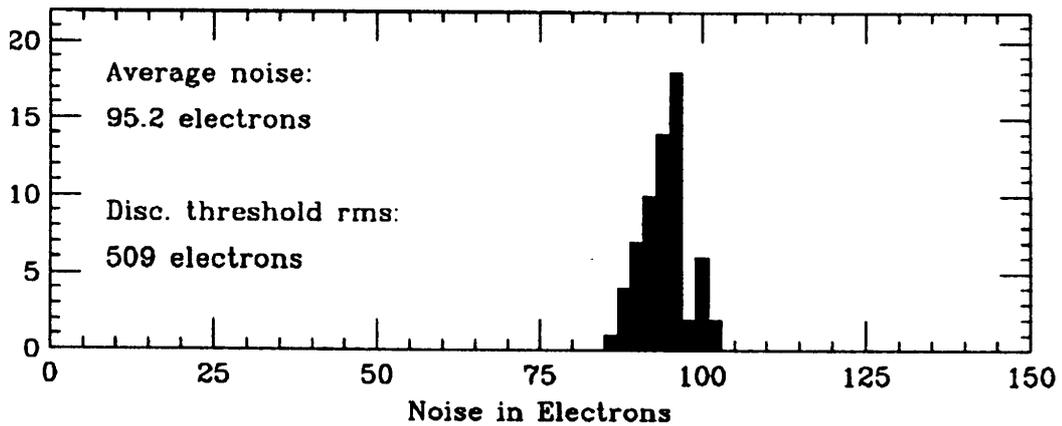
# Noise in Pixel Cells

Fermilab chip FPIX0 12 x 64 50 x 400  $\mu\text{m}$

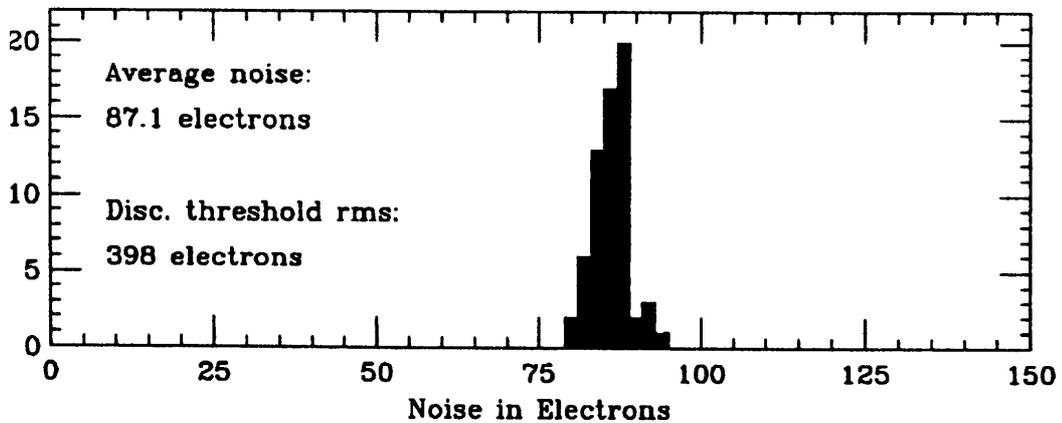
Measured Noise: Column 9 (bonded,  $C_f=10$  fF)



Measured Noise: Column 10 (bonded,  $C_f = 20$  fF)



Measured Noise: Column 11 (unbonded,  $C_f = 20$  fF)



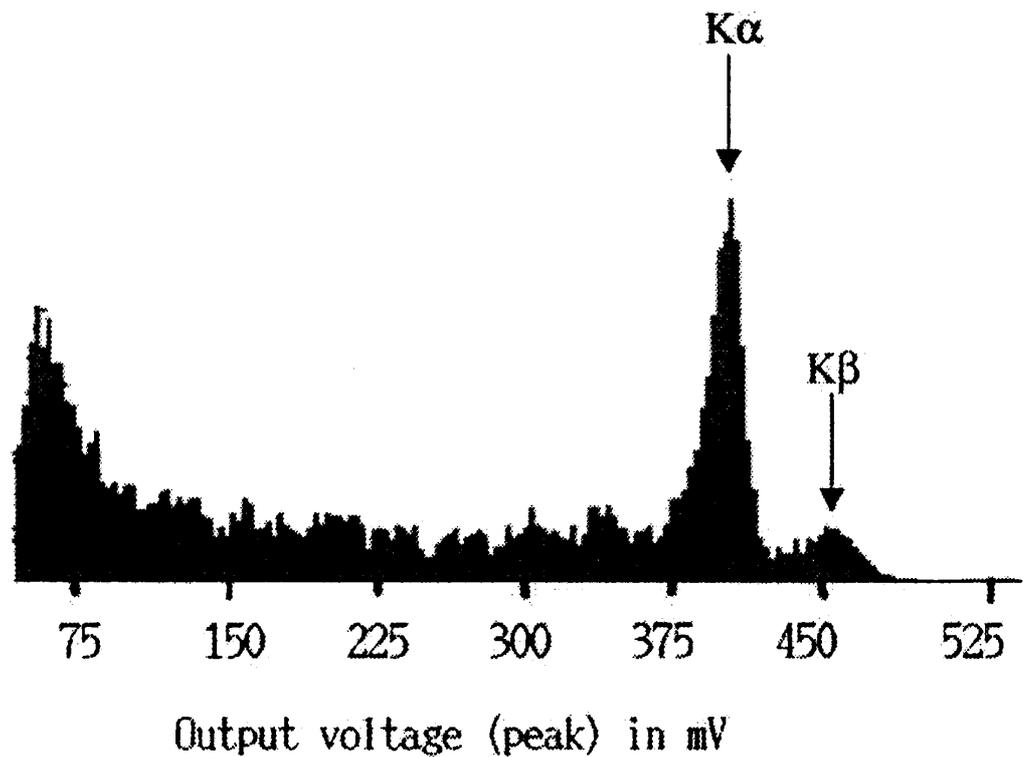
Noise measured from comparator response curve

# Noise in Pixel Cells

## Fermilab chip FPIX0

Absolute measurement  
using peak detector and direct output

80 - 100 e<sup>-</sup> rms



**44.5 keV K $\alpha$  X-ray Fluorescence from Tb**

# **Pixel Detectors : Dream or Nightmare ?**

**Not yet the moment for conclusion**

**Users in experiments convinced  
pixels allow access to new physics**

**Needed efforts sometimes underestimated**

**Common pool of know-how might help**

**Early contacts with industry about  
prospects for available technology**

**Pixels are more powerful for tracking than  
eg bubble chambers, much less investment**