POSITION SENSITIVE (SEMICONDUCTOR) DETECTORS PSD : APPLICATIONS in PARTICLE PHYSICS

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Liverpool
16 September 2005

PSD : NEW DETECTORS, NEW PHYSICS, NEW LIFE

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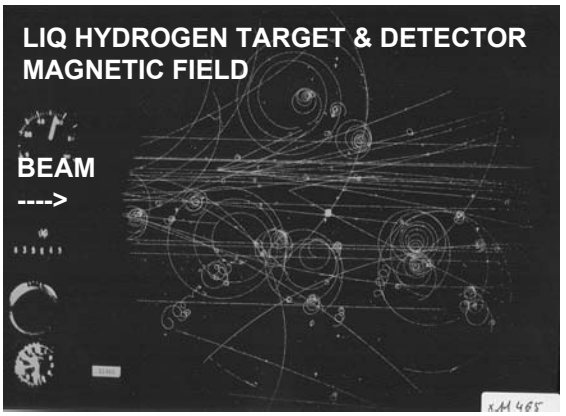
PSD or IMAGER ?

PARTICLE PHYSICS EXPERIMENTS
LOOK at EVENTS in 3D **CERN BUBBLE CHAMBER ~ 1970**



INSTANTANEOUS INTERACTIONS THAT WILL NEVER RE-OCCUR in EXACTLY SAME GEOMETRY
CAN 'SEE' NEW PARTICLES, NEW PHYSICS

OUTLINE

- PARTICLE PHYSICS EXPERIMENTS and the LHC

- HISTORICAL PERSPECTIVE :
DETECTOR DEVELOPMENT CRUCIAL to SEE NEW PHENOMENA
EVOLUTIONS vs JUMPS into NEW CONCEPTS
BUT : MUCH WORK NEEDED from CONCEPT to OPERATIONAL INSTRUMENT

- NEW PHYSICS at the LHC and BEYOND
NEW DETECTORS NEEDED ?

- MINIATURIZATION and PORTABILITY : DEMO Medipix2

LARGE HADRON COLLIDER

GIGA-DETECORS being INSTALLED for p-p COLLIDER EXPERIMENTS
EACH has CLOSE to 10^9 SENSOR ELEMENTS

GIGANTIC EFFORT is UNDERWAY
ALL AROUND THE WORLD

THOUSANDS of TRACKS each 25 ns

A VARIETY of POSITION SENSITIVE DETECTORS

SIGNAL PROCESSING, DATA TRANSMISSION, INFORMATION EXTRACTION

ELEMENTARY PARTICLE PHYSICS

AIM OF PARTICLE PHYSICS IS UNDERSTANDING OF MATTER and FORCES

MANY THINGS ARE KNOWN BY NOW
MOST INTERACTIONS 'TRIVIAL'
NEW PHENOMENA **MUST BE** STUDIED
AGAINST LARGE BACKGROUND

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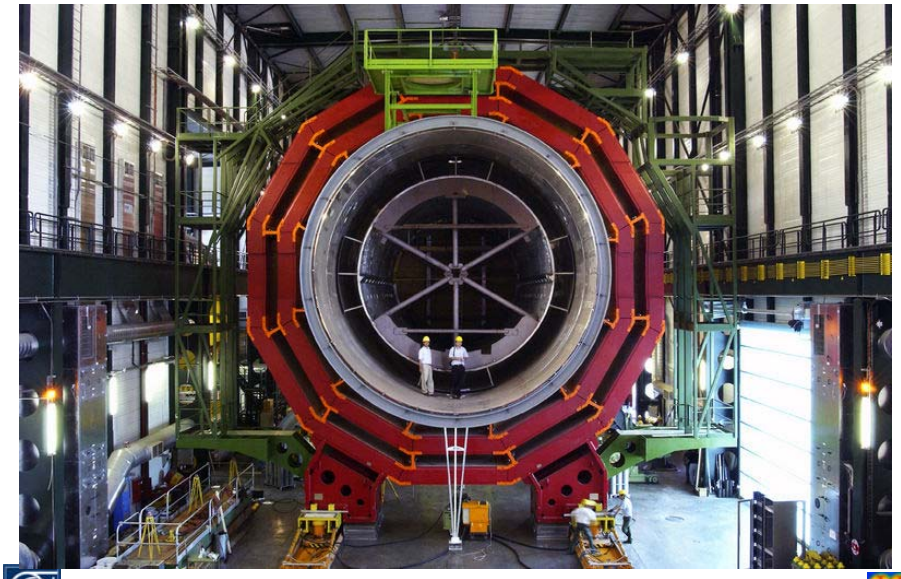
AGAINST LARGE BACKGROUND

SELECTIVITY FOR 'GOOD' EVENTS
HOW ? LARGE TRANSVERSE ENERGY, JETS
B-MESONS 'MESSENGER' FOR MANY
CRUCIAL PHENOMENA : DECAY VERTEX

CMS AXIAL VIEW of BARREL YOKE

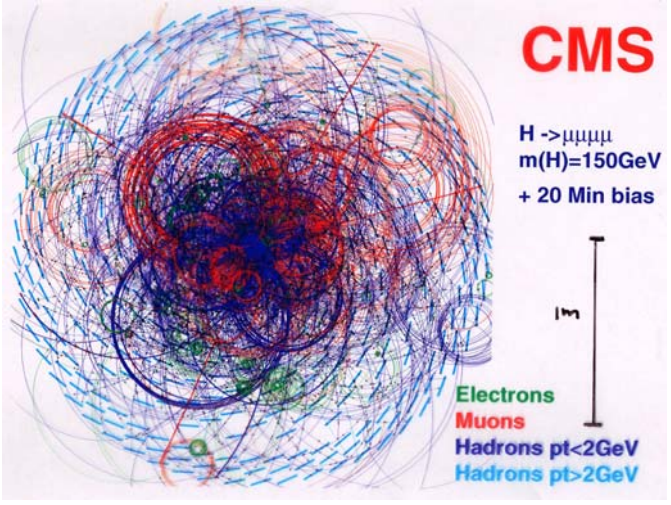


CMS SOLENOID

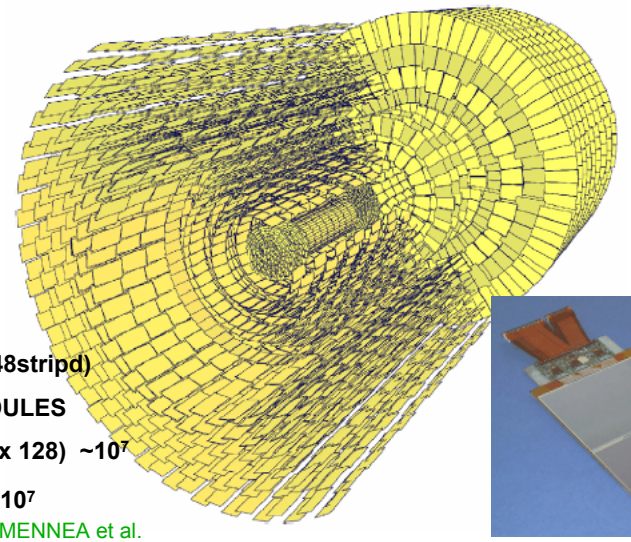
TO BE INSERTED in the YOKE
~ NOW FOR FULL TEST

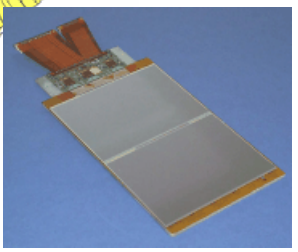
ONE BEAM CROSSING in TRACKER

out of 4×10^7 sec^{-1}



CMS SILICON TRACKER





16540 (15148stripd)

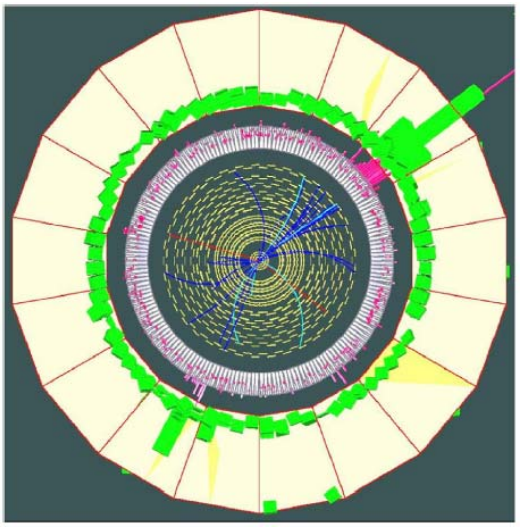
STRIP MODULES

(4-6 CHIPS x 128) ~10^7

PIXELS ~ $4x10^7$

M.S. MENNEA et al.
NIM A 548 (2005) 391

CMS DISPLAY

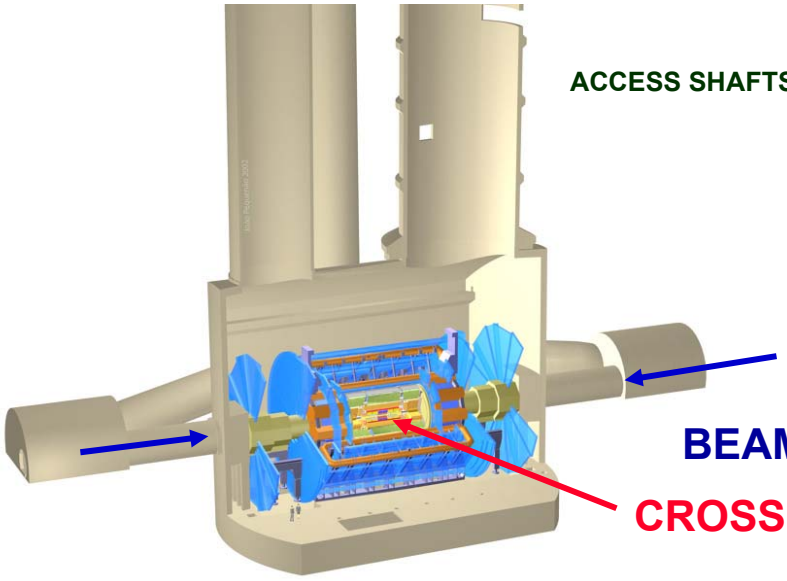


LAYERED 2D PROJECTION

PRELIMINARY

M.S. MENNEA et al.
NIM A 548 (2005) 391

ATLAS SITUATION UNDERGROUND



ONE WINDING of ATLAS TOROID

ATLAS COILS

LOWERING THROUGH SHAFT

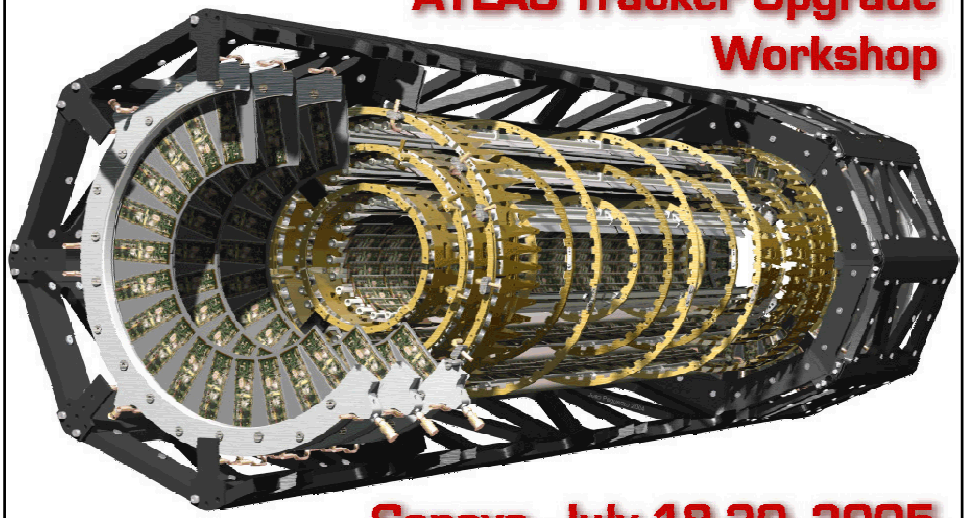
Prof Richard Wade - PPARC SHOWED
LAST MONDAY the still EMPTY CAVERN

MOVING IT IN PLACE

ATLAS : INSERTION of LAST SC COIL august 2005

ATLAS PIXEL TRACKER

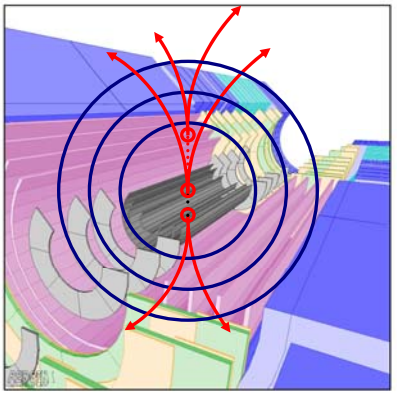
ATLAS Tracker Upgrade Workshop



Genova, July 18-20, 2005

ATLAS PIXEL TRACKER

L. Blanquart et al, Bonn Pixel 2005



NEEDED:

SEVERAL LAYERS

RADIUS ~ FEW CM ->

SPACE POINT PRECISION

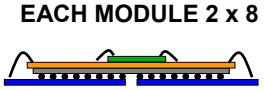
r_{phi} ~ 15 um

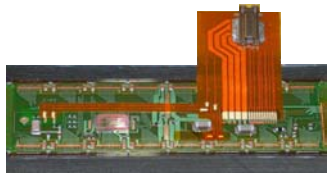
z ~ mm

MULTIPLICITY (n) per cm²

TIME RESOLUTION < 25 ns

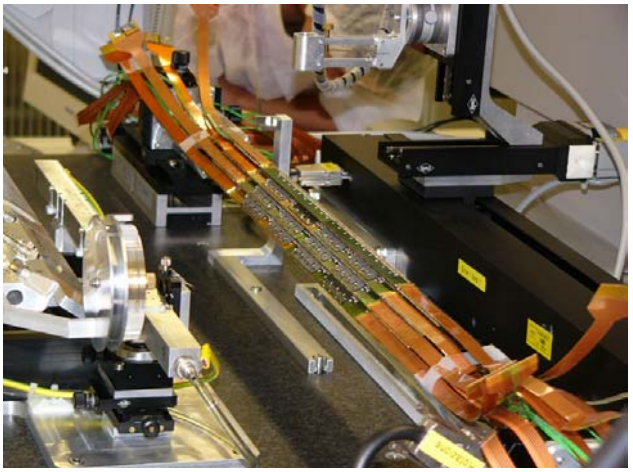
EACH MODULE 2 x 8 CHIPS



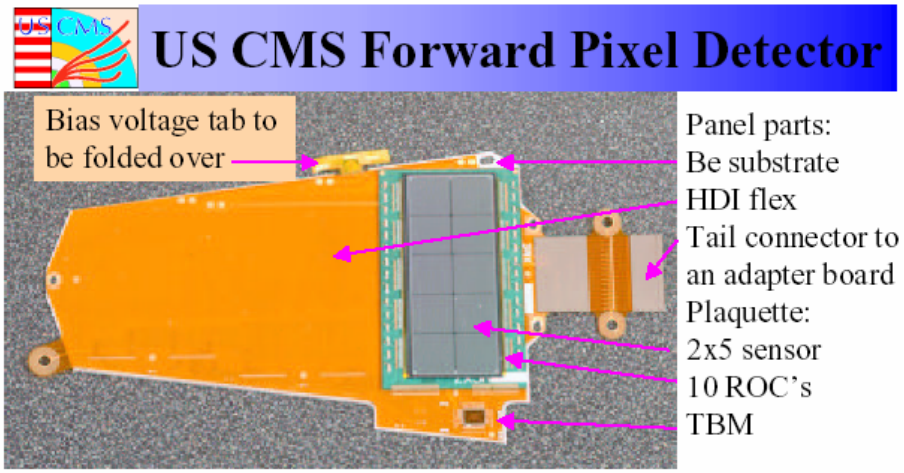


ALICE PIXEL TRACKER

Petra Riedler et al, Bonn Pixel 2005



CMS PIXEL TRACKER



M. Kubantsev, Northwestern Univ.
Bonn Pixel 2005

A HISTORICAL PERSPECTIVE

HOW TO SEE ELEMENTARY PARTICLES ?

'MICROSCOPES' to study PARTICLE TRACKS & INTERACTIONS

GAS & WIRE (later MULTIWIRES)

SCINTILLATION LIGHT in TRANSPARENT SOLID

PHOTOGRAPHIC EMULSION PLATE

CONDENSATION in GAS

BUBBLES in OVERHEATED LIQUID

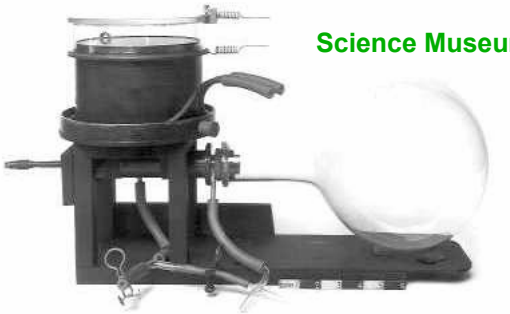
OPTICAL IMAGES

ELECTRICAL SIGNAL from IONIZATION :

MOVING CHARGES in GAS, LIQUID, SEMICONDUCTOR

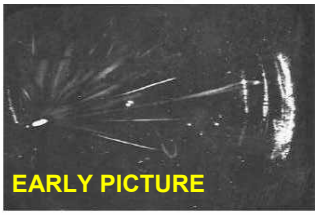
Erik HEIJNE CERN PH Department PSD Liverpool 16 September 2005

WILSON CLOUD CHAMBER

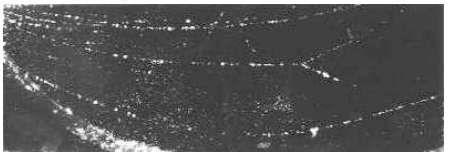


Science Museum London

MAIN IMAGING INSTRUMENT
1912-1950



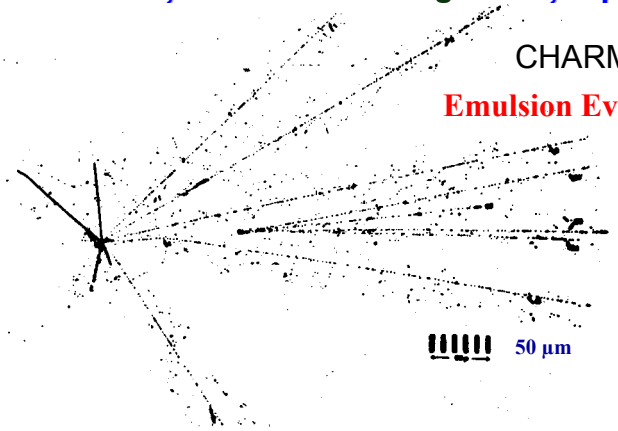
EARLY PICTURE



DISCOVERY of POSITRON
with CLOUD CHAMBER

NUCLEAR EMULSION TRACKING

SPECIAL, THICK FILM AgBr 3D, < µm PRECISION



CHARM DECAY

Emulsion Event WA59 ~ 1985

EARLIEST DISCOVERIES
NUCLEAR DECAY &
in COSMIC RAYS

STILL USED
(e.g. NEUTRINO EXP
GRAN SASSO)

EXTERNAL TRACKER
----> TRIGGERS

NO TIMING of EVENTS
LOW STATISTICS
NO SELECTIVITY

SEMICONDUCTORS

Si 'CHECKER BOARD' DETECTOR ~1965

SEGMENTED CONTACTS
REAR

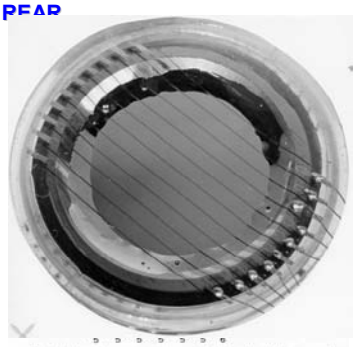
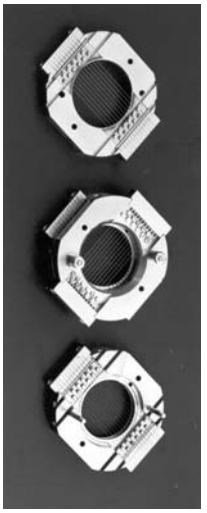


Fig. 2. Schematic representation of a Checkerboard detector with balanced read out system.

DOUBLE-SIDED FRONT & MASK with 100 µm WIRES

PHILIPS Patent
FILED 1967
THEY TRIED ION-IMPLANT
WAS UNRELIABLE THEN



TELESOPE
Si CHECKER BOARD
+ THICK Si(Li)

INVENTION of MONOLITHIC SEGMENTED DIODE

1.HARWELL: STRUCTURES on 1" SLICE

1958 not continuous

2.SACLAY: A FEW CONTINUOUS DIODES

1963 full charge collection

3.IKO/PHILIPS: FRONT/REAR STRIPS 1.2 mm (Hofker)

1965 projected 2-D US patent 1971

SEVERAL PROJECTS 1970 - 1980, ELECTRONICS is LIMITATION

4.CERN + ENERTEC, MUNICH TU + MPI

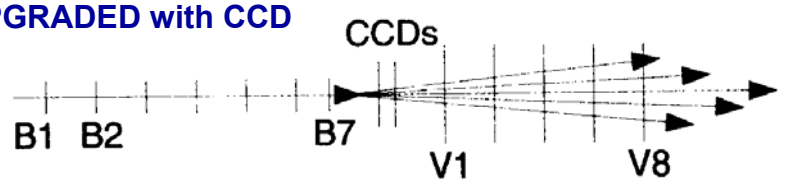
1980 smaller dimensions 200 um, 50 um

ion implantation (Kemmer, Burger)

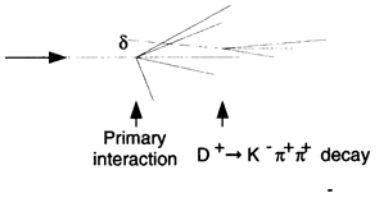
matched (micro) electronics !!!!

NEW DETECTORS for CHARM and B

NA11
UPGRADED with CCD



ORIGINAL PROPOSAL USED WIRECHAMBERS
FIRST UPGRADE Si MICROSTRIP DETECTORS
CERN & MPI (Kemmer, Klanner, Lutz, Heijne, Jarron, Burger, ..)
SECOND UPGRADE CCD RAL (Damerell, Watts)

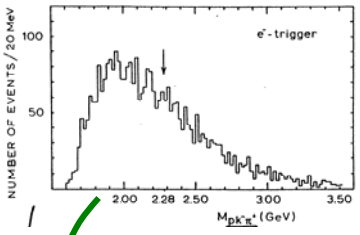


SELECTIVITY through TRACKING and SECONDARY VERTEX

CHARMED PARTICLE RECOGNITION

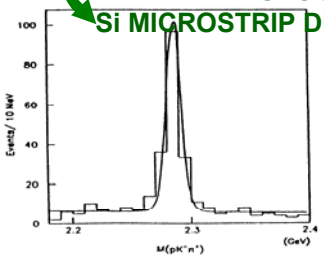
NA11 CHARM EXP

Λ_c --> p $K^-\pi^+$



INVARIANT MASS DISTRIBUTION
LARGE STATISTICS / 'NO' SELECTIVITY

NEW TECHNOLOGY :
Si MICROSTRIP DETECTORS + CCD



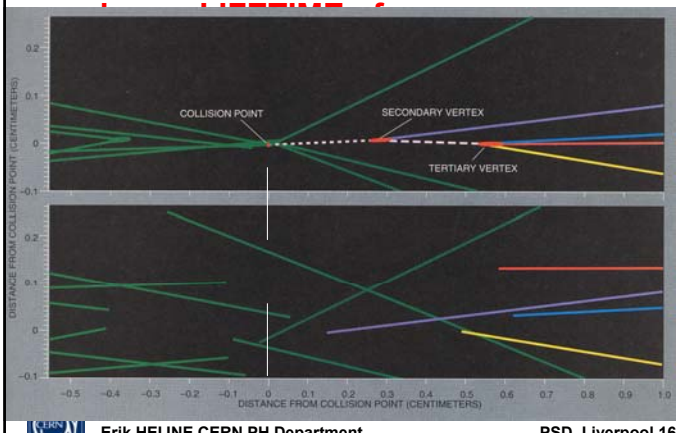
REDUCED BACKGROUND
MUCH HIGHER SENSITIVITY
CAN RUN at LOWER BEAM INTENSITY

DRAMATIC IMPROVEMENT !

ALEPH B- event

TRACKS WITH Si PLANES :

SECONDARY and TERTIARY VERTEX
BECOME APPARENT --> Bottom Particle
-> $e^- \nu_e$ then -> $\phi\ \pi^+$ ϕ–>K^+K^-



Si OFF-LINE :
SEE SEC, TER VERTEX

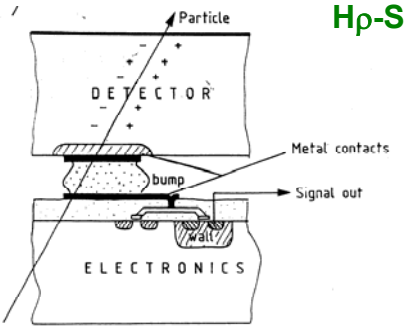
GAS TPC ALONE :
NOT ENOUGH
INFORMATION
TO FIND SEC VERTEX

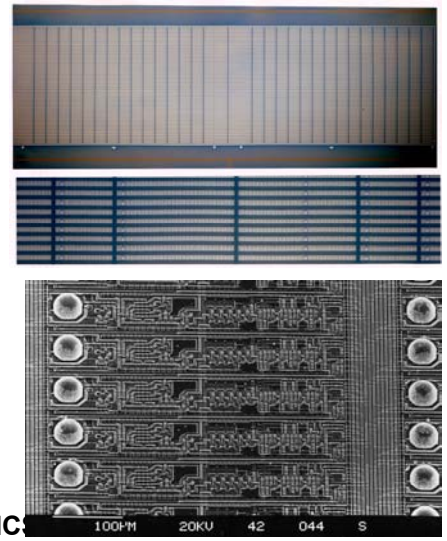
HYBRID Si PIXEL SENSOR 1991

CERN : CAMPBELL, HEIJNE

SENSOR MATRIX TRUE 2 - D

Hp-Si



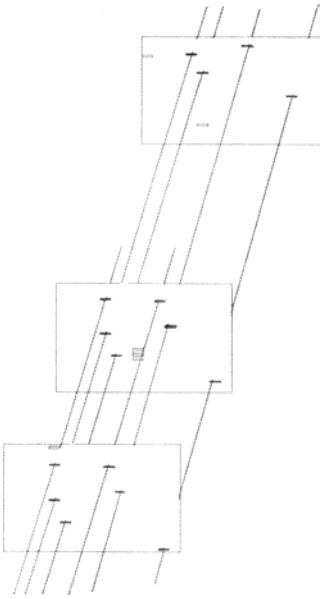


BUMPS

+

CMOS READOUT ELECTRONICS

FIRST TRACK RECONSTRUCTION PIXELS 1991



OMEGA TEST Sept 1991

1006 pixels 75 µm x 500 µm

3 ASSEMBLIES

BEHIND TARGET Pb ION BEAM

-> HIGH MULTIPLICITY

2-D, NO AMBIGUITIES

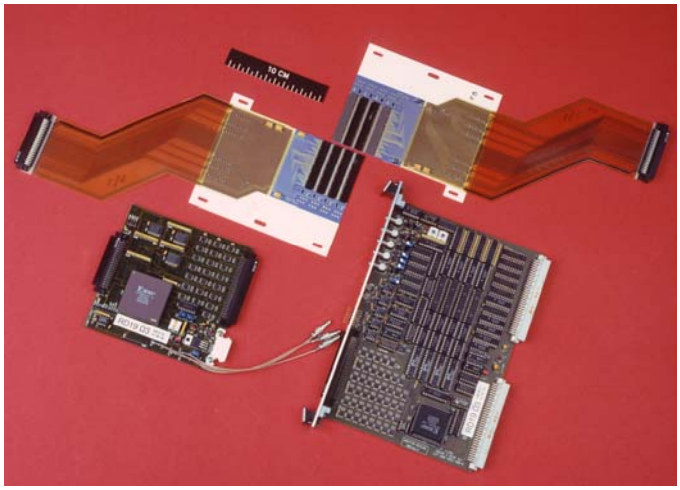
EVEN with > 10 TRACKS cm^{-2}

MUCH HIGHER INTENSITY POSSIBLE

MUCH BETTER SIGNAL / NOISE

(Heijne, Catanesi, Sauvage)

LHC1 PIXEL ARRAYS ~ 1995

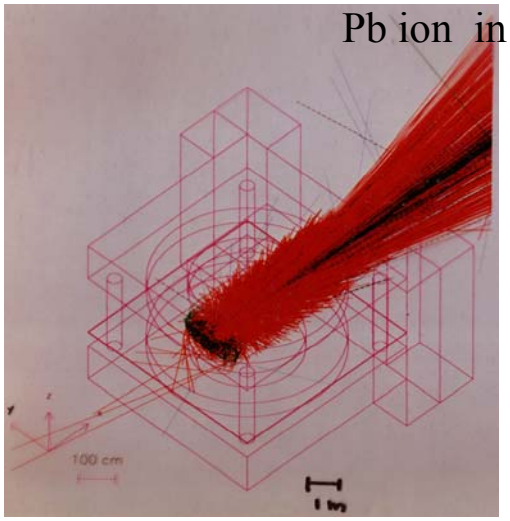


2 x 4 LADDERS
with OVERLAP
COVER 5 x 5 cm^2

14 PLANES
BUILT 1992 - 97

PIXEL TELESCOPE USED in CERN
RD19 DEVELOPMENT for LHC

FIXED TARGET EXPERIMENT HEAVY-ION EVENT



Pb ion in OMEGA spectrometer
RD19 +
WA97 / NA57

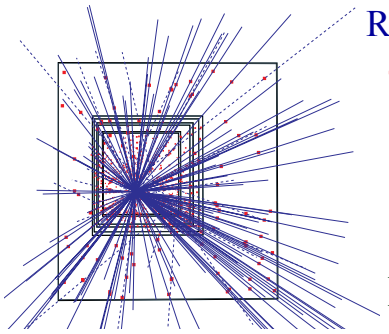
VERY HIGH MULTIPLICITY
TRACKING ONLY POSSIBLE
by NEW PIXEL TELESCOPE

IN OMEGA MAGNET
LATER IN GOLIATH

TRACKING with PIXELS at CERN

1995

WA97



RD19

7 PLANES
1.1 M pixels

153 tracks

B-field OFF

^{208}Pb ion at 158 A GeV/c on Pb target

Millions of EVENTS ANALYZED

SPACE POINTS
NOISE-FREE

DEMO MEDIPIX2

PSD 1 MICROPATTERN DETECTOR, A DREAM

PSD 7 IT IS NOW A DEMO

MEDIPIX2 MUROS2 NIKHEF vs USB PRAGUE

MUROS2 also needs
+ SENSOR BIAS
+ Nat Instr DAQ CARD
in PC

REDUCTION in
SIZE
CABLES
POWER

CAPABILITY in SPEED
few Hz

Stanislav Pospisil, Jan Jakubek, Thomas Holy, Zdenek Vykydal

MEDIPIX2 USB CLOSE-UP PRAGUE-CERN

BUMP-BONDED SENSOR (300 um)+ R/O

BIAS VOLTAGE up to 100V
generated in the USB (also external)

FILTERING FAR TOO BIG NOW
USE SMALLER CARD & COMPONENTS

COMPLETE USB PROCESSOR
in MINI BOX, serial 0003

STANDARD USB CABLE to NOTEBOOK

Stanislav Pospisil, Jan Jakubek,
Thomas Holy, Zdenek Vykydal

MINIATURIZATION MEDIPIX2 USING USB

PRAGUE-CERN

SHORT INTERMEZZO :

TRY to APPLY RECENT INDUSTRY TRENDS to SCIENTIFIC INSTRUMENTS

1997 : MEDIPIX1 DETECTOR READOUT with VME CRATE (Pisa, Laben SpA) +++ etc

2000 : MEDIPIX1 READOUT with MUROS (NIKHEF) + Nat.Instr. Card in PC, MediSoft

2003 : MEDIPIX2 READOUT MUROS2 (NIKHEF) faster, + NI card, quad/octet, MediSoft

2005 : USB + PC + Pixelman (IEAP - CTU Prague) **NEW**

WORK by Stanislav Pospisil, Jan Jakubek, Thomas Holy, Zdenek Vykydal

MEDIPIX2 PARTNERS

- U INFN Cagliari
- CEA-LIST Saclay
- CERN Genève
- U d'Auvergne Clermont
- U Erlangen
- ESRF Grenoble
- U Freiburg
- U Glasgow
- IFAE Barcelona
- Mitthoegskolan
- MRC-LMB Cambridge
- U INFN Napoli
- NIKHEF Amsterdam
- U INFN Pisa
- FZU CAS Prague
- IEAP CTU in Prague
- SSL Berkeley

http://medipix.web.cern.ch/MEDIPIX/

SPOKESMAN Michael CAMPBELL
Deputy Jan VISSCHERS

ISSUES in TRACKING

2-D SEGMENTATION in PIXELS --> 3D VOXELS

SPACE POINTS ~ 10 µm

LOW CAPACITANCE <100 fF

-> NOISE 50 - 100 e^- rms

-> THIN SENSOR 50 µm ?

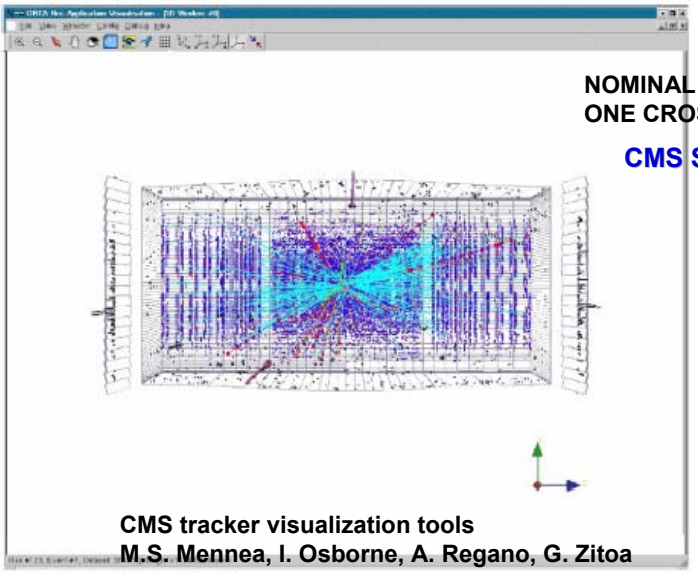
-> SPEED signal < 10 ns

VERY HIGH MULTIPLICITY

> 10 coincident particles cm^{-2}

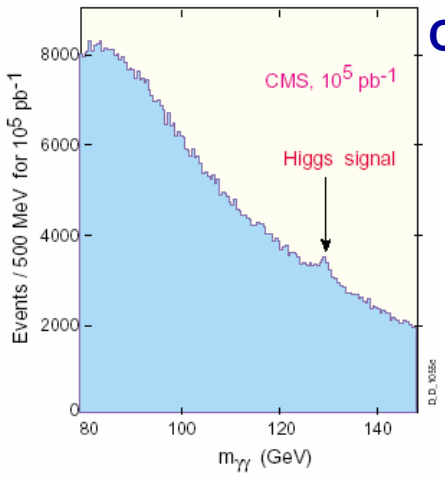
ON-CHIP INTELLIGENCE TRIGGER INFO

BACK at LHC



CMS tracker visualization tools
M.S. Mennea, I. Osborne, A. Regano, G. Zitoa
Nucl Instr Meth A548 (2005) 391

SIGNAL and BACKGROUND



CMS

$H_{SM} \rightarrow \gamma\gamma$

Simulated 2γ mass plot
for 10^5 pb^{-1} m_H =130 GeV
in the lead tungstate calorimeter

PESSIMISTIC ?

WILL IT BE POSSIBLE TO IMPROVE SIGNAL OVER BACKGROUND

SELECTIVE FOR 'GOOD' EVENTS
REJECT BACKGROUND EVENTS

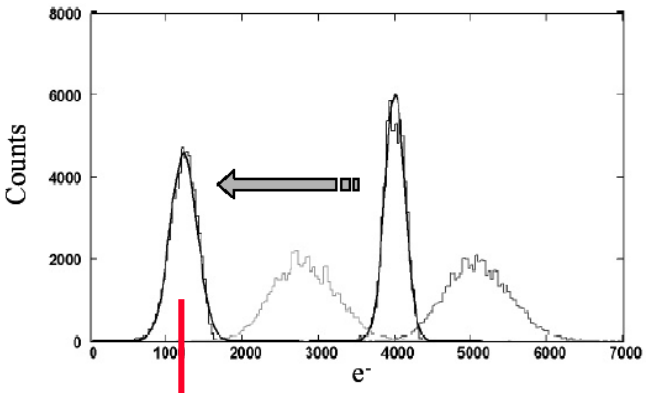
FUTURE DETECTORS

AIM AT HIGH RATE, HIGH MULTIPLICITY HADRON PHYSICS

ELECTRON / PHOTON EXPERIMENTS SEEM 'EASIER'

NEUTRINOs, COSMIC RAYS, AXIONs, OTHERS ?

LOW SIGNALS CAN BE EMPLOYED



MEDIPIX2
SMALL PIXEL CELL
55µm x 55µm

LOW NOISE
LOW THRESHOLD
BINARY DETECTION

THIN DETECTOR
LOW RESISTIVITY :
AT ROOM TEMP
LESS DAMAGE

TRIMMED THRESHOLD can be MOVED to ~LOWEST VALUE

1100 e^- or 4 keV in Si

GENERATED by M.I.P. in ~25 µm Si

THIN WAFERS and THROUGH VIA

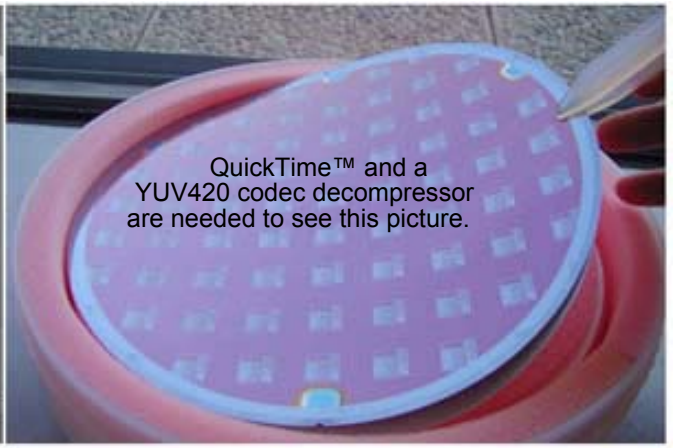
IMEC

VIA 2 um

PROCESSED WAFER, THINNED to 50 um

THIN WAFERS and THROUGH VIA

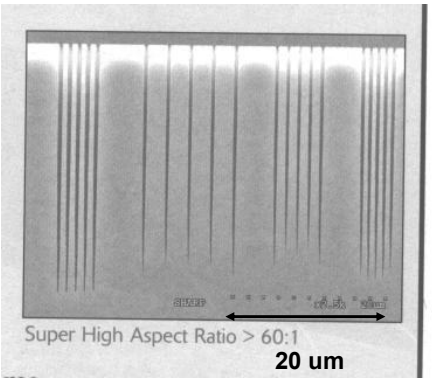
IME
C

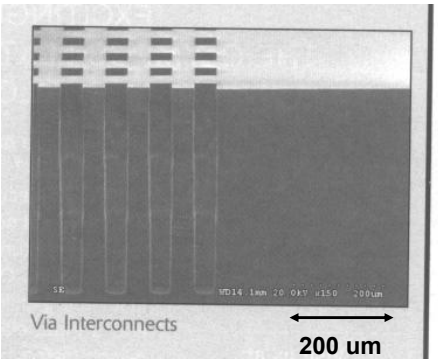


VIA 2 um **PROCESSED WAFER, THINNED to 50 um**

THROUGH -WAFER VIA

NEW PLASMA ETCHING EQUPMENT



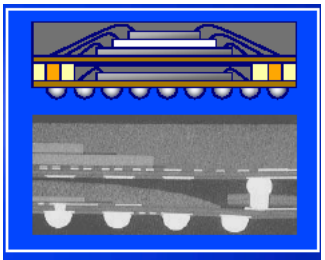


ALLOWS 3-DIMENSIONAL STRUCTURES

SEVERAL LAYERS of PROCESSING / SENSING

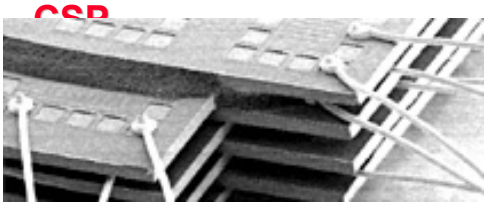
ASPECT RATIO
60 : 1
ADIXEN (ALCATEL) 2005

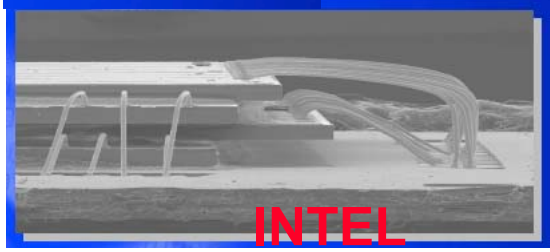
3D VERTICAL INTEGRATION



SP-CSP
(330 signals)

CHIP SCALE PACKAGE
CSP

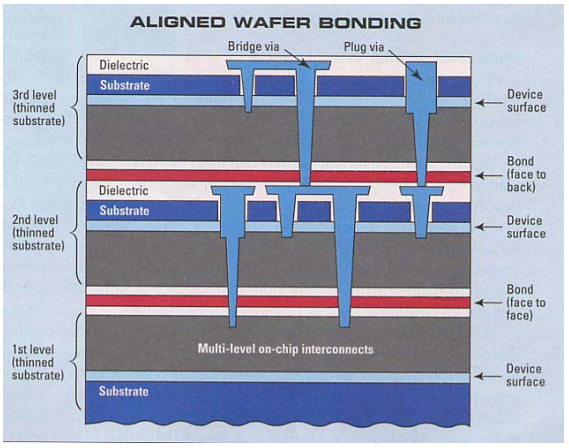


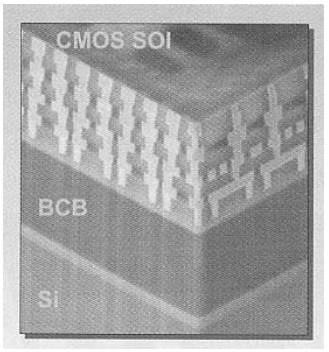


Challenges

- Bonding to "floppy" die overhang
- Manage wiresweep
- Minimize wirebond pad area

MULTI LAYER WAFER ASSEMBLY



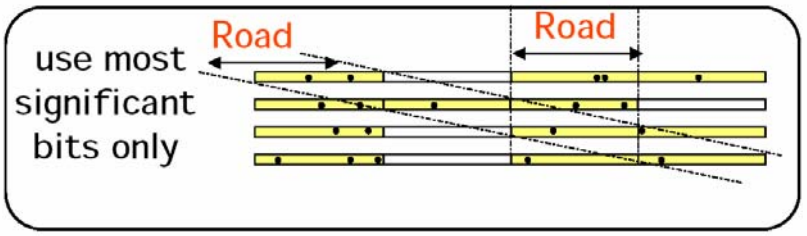


SOI is ALREADY 2 LAYERS

SOFTWARE or also HARDWARE ?

FAST-TRACK COLLABORATION

USE MICROPROCESSORS for FAST TRIGGER



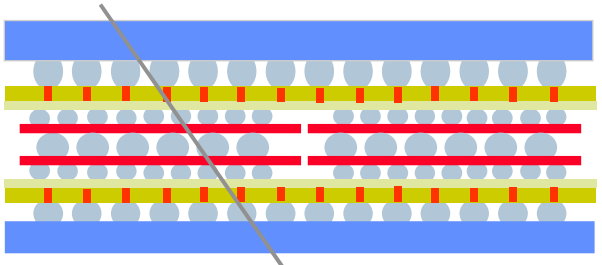
MULTI-LAYER-DETECTOR with LOCAL PROCESSING :

SPACE-POINT + VECTOR

VERTEX SELECTION, BACKGROUND SUPPRESSION, ..

TRACK VECTOR DETECTOR

3D TECHNOLOGY* MULTILAYER ASSEMBLY



PROVIDES X , Y , Θ_X , Θ_Y

intersecting position + angular direction

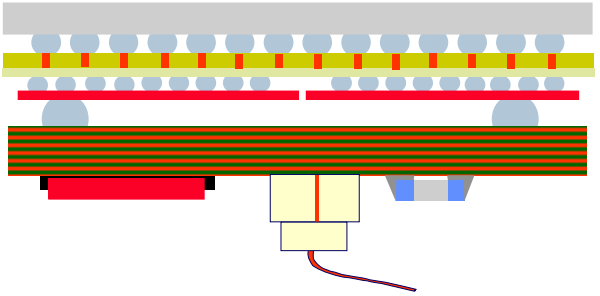
MAY ALLOW TO PINPOINT INTERACTION POINT 'ON-LINE'

3D-STACKED IMAGING TILE

DESIGN FOR X-RAY IMAGING
NOT OPTIMIZED FOR TRANSPARENCY

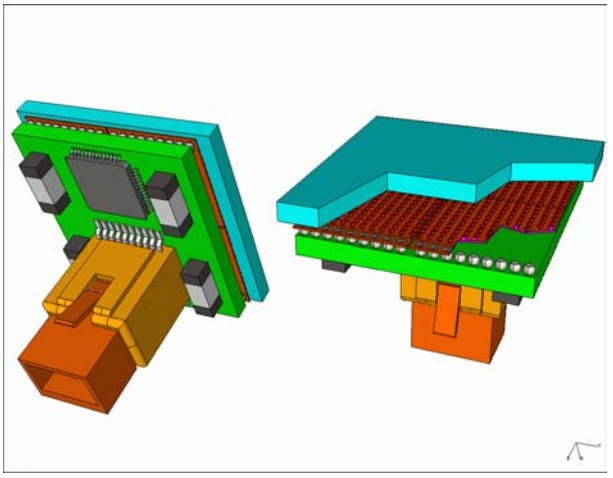
Basic image cell : vertical hybridisation of: sensor,
Read-out electronics & Interface circuitry & connector
Typical size: 20 x 20 mm^2

CONCEPT :
JAN VISSCHERS
NIKHEF



sensor
interposer
CMOS chips
carrier
passives

PIXEL SENSOR INTEGRATION/TILING



CONCEPT :
JAN VISSCHERS
NIKHEF

INSPIRATION for FUTURE DETECTORS

MICROELECTRONICS TECHNOLOGIES for COMMUNICATION

USE THESE also for NEW PHYSICS

BETTER DETECTION of 'GOOD' TRACKS
IDENTIFY BEAUTY also inside JETS
IMPROVE SELECTIVITY at HIGH RATES
super LHC or FURTHER
TRACK VECTOR at ~200ns timescale
INTERACTION POINT FROM 20-100 along beam

THE END

THANKS to MANY COLLEAGUES OVER MANY YEARS
NO RESULTS WOULD BE THERE WITHOUT THEM

CERN
CERN MICROELECTRONICS GROUP
EXPERIMENTS
MEDIPIX COLLABORATION
INDUSTRIAL COMPANIES
RESEARCH INSTITUTES in EUROPE, USA, JAPAN

CONCLUSION

R&D MUST BE AMBITIOUS

PREPARE ANSWERS TO FUTURE CHALLENGES EVEN UNKNOWN

USE INDUSTRY TRENDS in Si towards '3D'

INVESTIGATE VECTOR DETECTOR

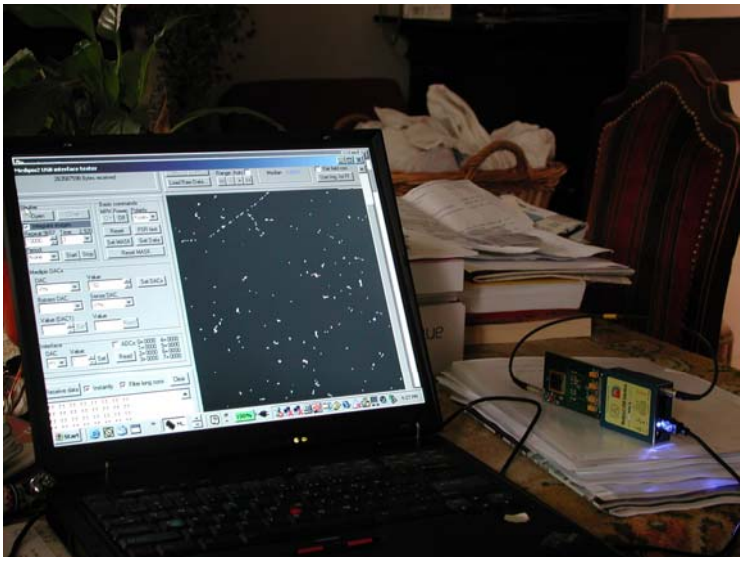
GASEOUS or SEMICONDUCTOR

R&D MUST INCLUDE SYSTEM ASPECTS

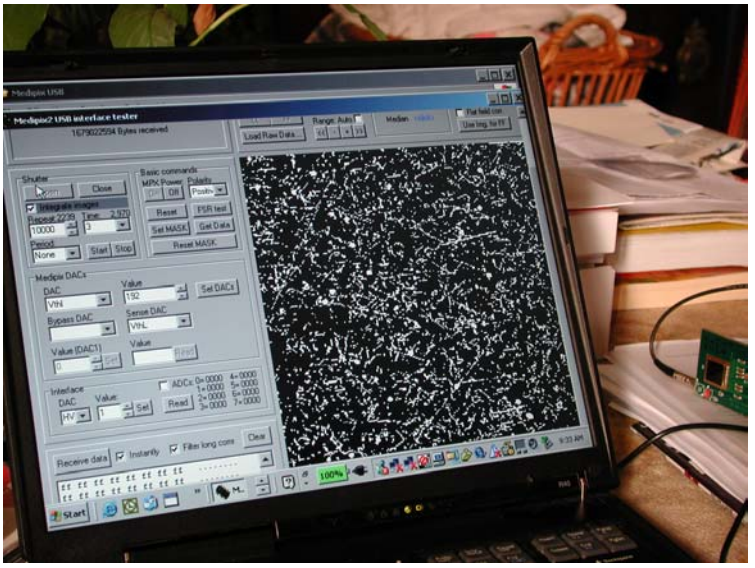
ON-LINE, OFF-LINE ANALYSIS OTHER WORLD

THE END - BACKUPS

COSMIC RAYS with MEDIPIX2-USB



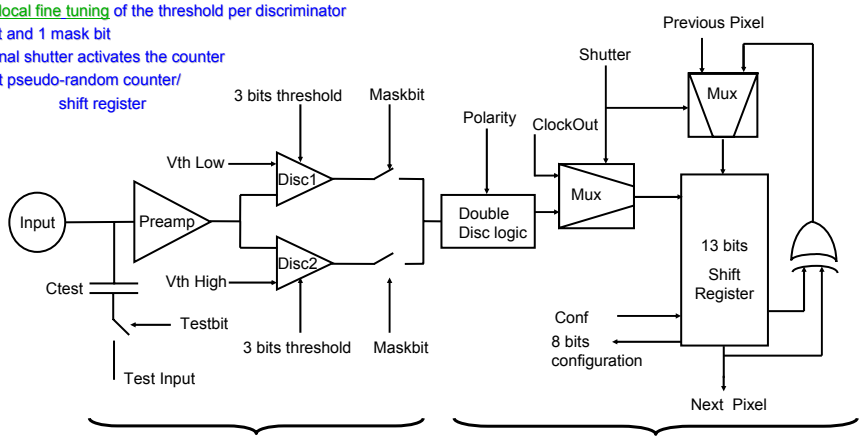
MEDIPIX2-USB COSMICS



MEDIPIX2-USB + LARGE BACKGROUND

MEDIPIX2 PIXEL BLOCK DIAGRAM

accepts positive and negative input → different detector materials
charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and 1 mask bit
external shutter activates the counter
13-bit pseudo-random counter/
shift register



Medipix2 PIXEL CELL LAYOUT

CMOS technology 0.25µm

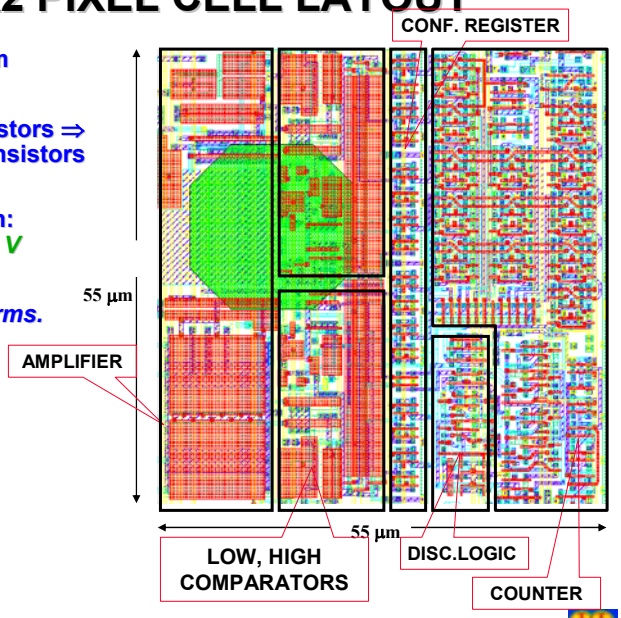
6 metal layers

pixel cell has ~500 transistors ⇒
chip ~33 million transistors

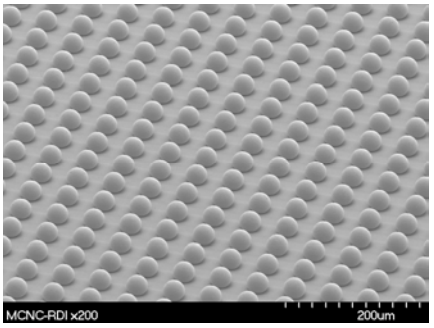
Static power consumption:
~8µW/channel @ 2.2 V

Amplifier Gain: ~11 µV/e⁻

Electronic Noise: ~100 e⁻ rms.



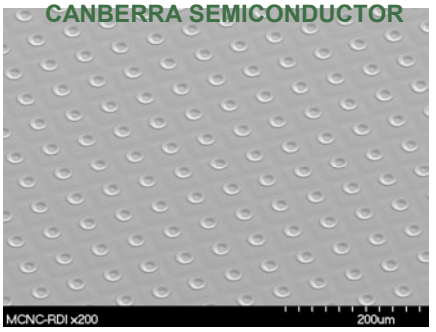
BUMP BONDING Medipix2



BUMP DEPOSITION
& SEM PHOTOS
COURTESY MCNC-RDI DURHAM NC

PITCH 55 µm

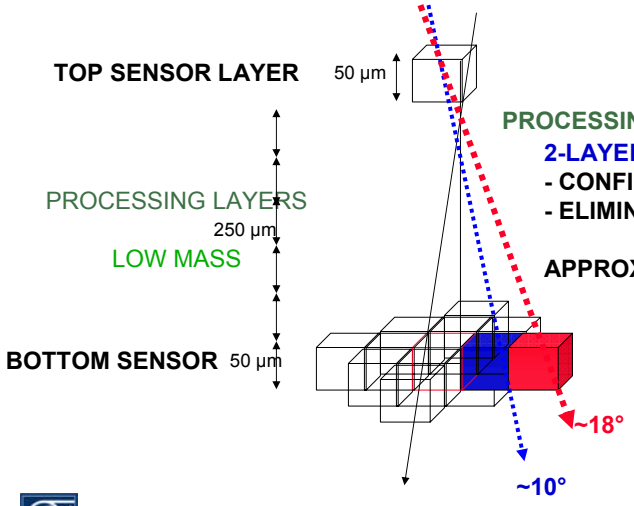
HIGH RESISTIVITY
Si SENSOR MATRIX
CANBERRA SEMICONDUCTOR



0.25 µm CMOS CHIP
CERN 2001
CAMPBELL & LLOPART
256 COLUMNS x 256 ROWS
pixel 55µm x 55 µm

SMALLER PIXELS

50 x 50 x 50 µm → **SIGNALS ~ 3000 e^-**



PROCESSING BETWEEN SENSORS

2-LAYER COINCIDENCE :

- **CONFIRMS TRACK STUB**
- **ELIMINATES PHOTON HIT, NOISE**

APPROXIMATE VECTOR

THE END

OTHER APPROACH CHIP COOLING

WAFERS are FUSED after ETCHING CHANNEL

DIRECT CONTACT
Si is GOOD CONDUCTOR