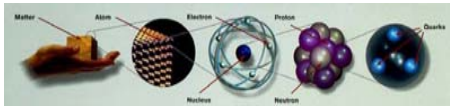
GIGASENSORS for ATTO OBJECTS

ERIK H.M. HEIJNE
CERN Genève

STW Veldhoven
17 November 2005

SMALLER and SMALLER



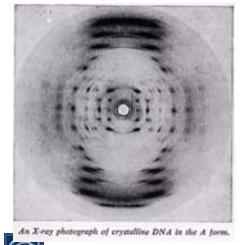
SCANNING ELECTRON MICROSCOPE

POLYGONUM
'KLEEFKRUID'

POLLEN
DIAMETER 50 um

SCIENCE PHOTO LIBRARY / Malin, Phaedon

MOLECULAR STRUCTURE by X-RAY LIGHT DIFFRACTION



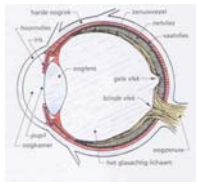
DISCOVERY of DNA
~ 1952
from J.D. WATSON
'The Double Helix'

FILM as SENSOR
LONG HISTORY
VERSATILE
ARCHIVING

MICROSCOPIC IMAGING INSTRUMENTS

POCKET-SIZE TECHNOLOGY TO LOOK DEEPER THAN HUMAN EYE

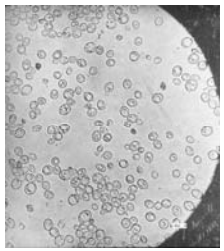
SINGLE LENS
around 1670



DISCOVERIES ⟷ NEW INSTRUMENTS
TECHNOLOGY SPIRAL
Casimir

Museum Boerhaave Leiden

OPTICAL MICROSCOPE

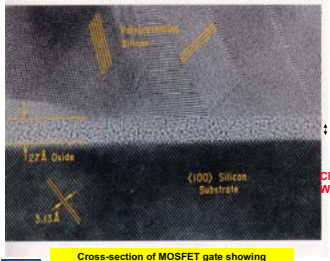


BEER YEAST
Saccharomyces cerevisiae

Léon FOUCAULT
~ 1844
CELL DIMENSION
~ 70 um

Soc Fran. de Photogr. / Malin, Phaedon

ATOMIC FORCE MICRO-'nano'-SCOPE



↕ 1 nm

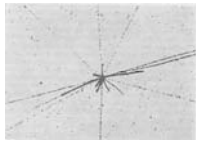
CRYSTAL LATTICE
WITH SINGLE ATOMS

Cross-section of MOSFET gate showing thin isolation layer of SiO_2 (talk A. Marchioro)

VISUALIZATION below ATOMIC DIMENSIONS

SOME INDIRECT METHODS
ENERGY LOSS --> IONIZATION
GAS — GM COUNTER WILSON CHAMBER MWPC
LIQUID — BUBBLE CHAMBER LAr CALORIMETER
SOLID — PHOTO EMULSION SEMICONDUCTOR SENSORS
ENERGY LOSS --> LIGHT
GAS — FLUORESCENCE
LIQUID { SCINTILLATION
SOLID { CERENKOV RADIATION
NEUTRALS HAVE TO CONVERT TO BE SEEN

NUCLEAR EMULSIONS



3D TRACKER

GOOD EMULSIONS
MADE SINCE~ 1940

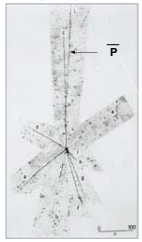
'STAR'
NUCLEAR DISINTEGRATION

IONIZATION DENSITY --> PARTICLE IDENTIFICATION
DECAY LENGTH --> PARTICLE LIFETIME

ANNIHILATION of ANTI PROTONS

Left: the first annihilation star imaged in the photographic-emulsion stack experiments, led by Gerson Goldhaber of the Segrè group, which confirmed the discovery of the antiproton. An antiproton enters from the top of the image and travels about 430 µm before meeting a proton. Nine charged particles emerge from the annihilation. Right: bubble-chamber image where an antiproton enters at the bottom. When it strikes a proton, four positive and four negative pions are created.

CERN COURIER Nov 2005

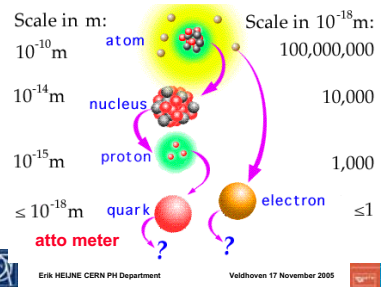


NUCLEAR EMULSIONS
1955 BEVATRON

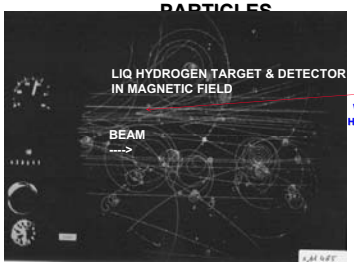
BUBBLE CHAMBER
Antiproton ->4 ± 4-

DIMENSIONS of ELEMENTARY PARTICLES

DIMENSIONS



HOW TO SEE ELEMENTARY PARTICLES

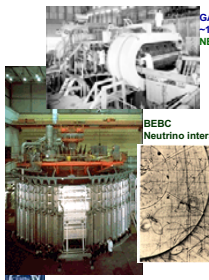


3D EVENTS

INTERACTION WITH STRAIGHT, HIGH MOMENTUM PRODUCTS

INTERACTIONS NEVER RE-OCCUR in EXACTLY SAME GEOMETRY

BUBBLE CHAMBERS to SEE ELEMENTARY PARTICLES



GARGAMELLE : LIQ PROPANE
~1973
NEUTRAL CURRENTS

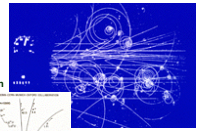
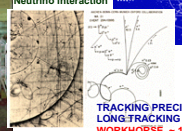


PHOTO from 2m CHAMBER LIQ HYDROGEN

BEBC
Neutrino interaction



TRACKING PRECISION ~ 1mm
LONG TRACKING DISTANCES -> MOM ENTU
WORKHORSE ~ 1960 - 1985
1 picture / some seconds

ATTO ?

MILLI
MICRO
NANO
PICO
FEMTO
ATTO

ATTO

MILLI
MICRO
NANO
PICO
FEMTO
ATTO 10^{-18}
10^{-21} ZEPTO
10^{-24} YOCTO

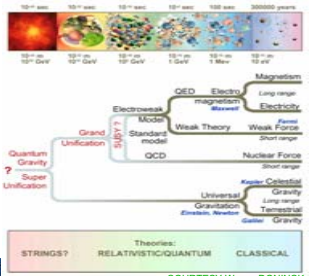
ATTO

MILLI
MICRO
GIGA NANO
TERA PICO
PETA FEMTO
10^{+18} EXA ATTO 10^{-18}
10^{+21} ZETTA ZEPTO
10^{+24} YOTTA YOCTO

MESSAGE

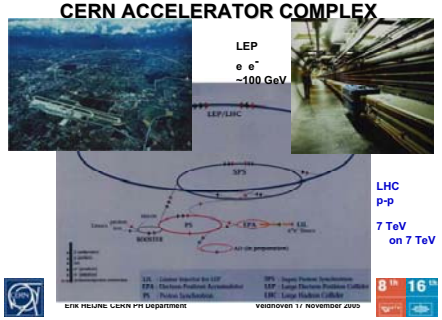
- HISTORICAL PERSPECTIVE
  SMALLER and SMALLER : MICRO, NANO, ATTO,..
  from MICROSCOPE to ATTOSCOPE
- PARTICLE PHYSICS EXPERIMENTS at the LHC
  Large Hadron Collider
- VARIETY of SENSORS
  MOMENTUM via TRACKING POINTS
  TOTAL PARTICLE ENERGY (via CHARGE or LIGHT)
  ENVIRONMENT (POSITIONS, TEMP, RADIATION DOSE, ..)
- A LOT of ELECTRONICS
  CUSTOM DESIGN FRONT- END CHIPS
  DATA TRANSMISSION to CONTROL ROOM
  WORLD-WIDE DISTRIBUTION and CONTROL (on/off

UNIFICATION



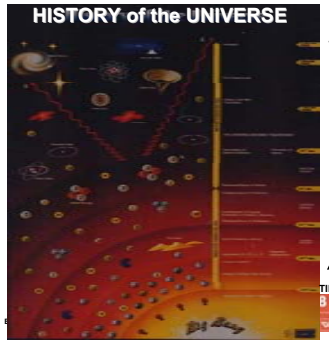
COURTESY W. van DONINCK

CERN ACCELERATOR COMPLEX

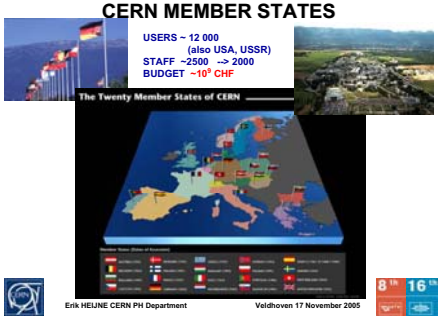


ELEMENTARY PARTICLES and EARLY UNIVERSE

HISTORY of the UNIVERSE

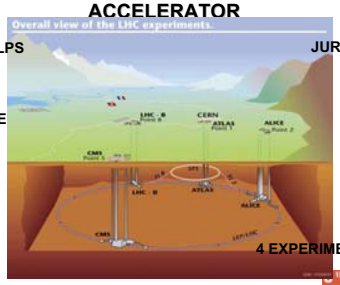


CERN MEMBER STATES



CERN – Particle Accelerators

CERN – UNDERGROUND ACCELERATOR



MICROSCOPE 10^{-6} m

ATTOSCOPE 10^{-18} m

NIKHEF / CERN

ATLAS MOVIE

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

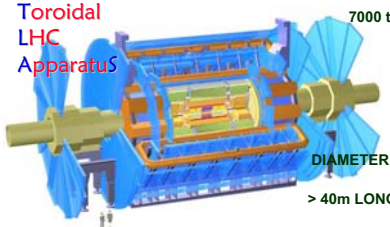
LHC in EMPTY LEP TUNNEL

ANIMATION

MAGNETS and CRYO-SUPPLY-LINE (He 4.2 K)

ATLAS MODEL

A
Toroidal
LHC
ApparatuS



LARGE NUMBER of SENSOR ELEMENTS > 10^8

http://atlas.web.cern.ch/Atlas/

LHC MAGNETS on PARKING

CERN PHOTO

LHC MAGNETS before DESCENT

CERN PHOTO

LHC MAGNETS in TUNNEL

MAGNETS and CRYO-SUPPLY-LINE (He 4.2 K) REAL

LARGE INSTRUMENT NEEDED

TO STUDY SMALLEST OBJECTS

γ photon with $\lambda = 10^{-18}$ m has energy ~1 TeV

HIGH FREQUENCY IMAGING NEEDED (40 MHz FRAME RATE)

LARGE INSTRUMENT NEEDED

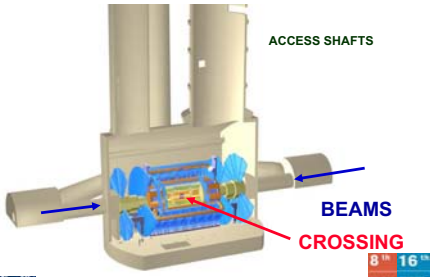
TO STUDY SMALLEST OBJECTS

γ photon with $\lambda = 10^{-18}$ m has energy ~1 TeV

HIGH FREQUENCY IMAGING NEEDED (40 MHz FRAME RATE)

HIGH RESOLUTION IMAGING NEEDED (< 10 μm precision)

ATLAS SITUATION UNDERGROUND



LARGE INSTRUMENT NEEDED

TO STUDY SMALLEST OBJECTS

γ photon with $\lambda = 10^{-18}$ m has energy ~1 TeV

LARGE INSTRUMENT NEEDED

TO STUDY SMALLEST OBJECTS

γ photon with $\lambda = 10^{-18}$ m has energy ~1 TeV

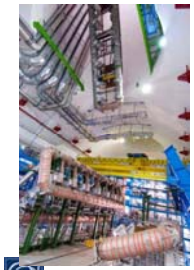
HIGH FREQUENCY IMAGING NEEDED (40 MHz FRAME RATE)

HIGH RESOLUTION IMAGING NEEDED (< 10 μm precision)

DIMENSIONS IMPOSED BY CONTAINMENT of HIGH ENERGY (TeV)

WINDING of ATLAS TOROID

ATLAS SUPERCONDUCTING COILS



LOWERING THROUGH SHAFT

MOVING IT IN PLACE

ATLAS : INSERTION of LAST SC COIL

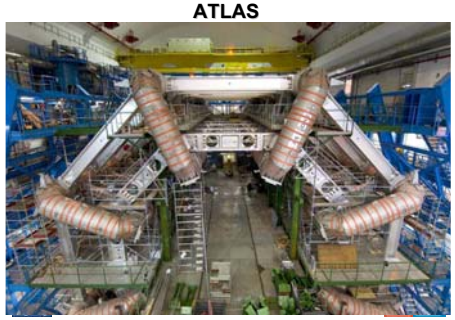
August 2005

THE OTHERS: CMS - VIEW of BARREL

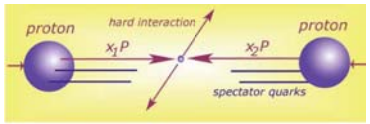
COMPARISON ATLAS - CMS

COURTESY W. van DONINCK

ATLAS



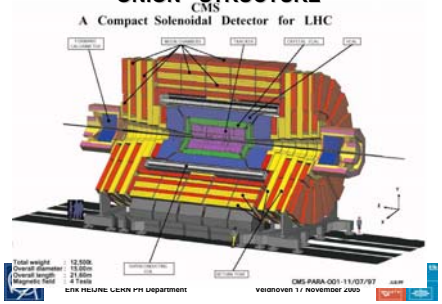
STUDY NEW PHENOMENA



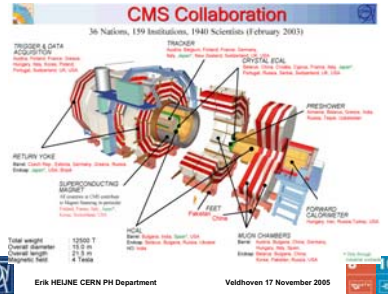
HIGH ENERGY NEEDED
SMALL CROSS SECTIONS FOR NEW PHENOMENA
HIGH INTENSITY
yet LOW RATE of 'GOOD' EVENTS
SELECTIVITY in TRIGGER

COURTESY
STAN BENTVELSEN

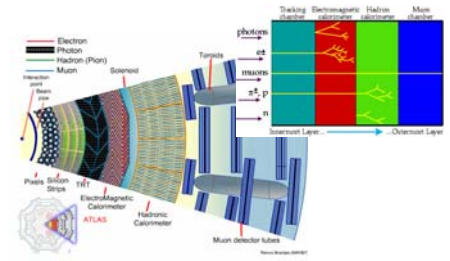
ONION - STRUCTURE



LHC – Compact Muon Solenoide (CMS)



SENSOR LAYERS ATLAS



COURTESY
STAN BENTVELSEN cs

MULTITUDE of SENSORS

MOMENTUM MEASUREMENT via TRACKING
'EMPTY' INNER REGION : GAS or THIN
SILICON also : CERENKOV RINGS

MUONS are MESSENGER PARTICLES
TRAVERSE THICK LAYERS
OUTER WIRE CHAMBERS

TOTAL ENERGY MEASUREMENT
ELECTROMAGNETIC SHOWERS
HADRONIC SHOWERS
LIGHT COLLECTED from HEAVY CRYSTALS
CHARGE in LIQUID ARGON

CUSTOM CHIP DESIGN

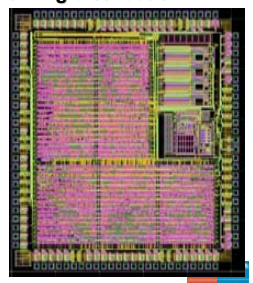
MOST CHIPS in 0.25 µm CMOS

40 MHz
LOW POWER
RESTRICTED SPACE, COOLING

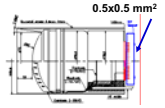
HIGH RADIATION ENVIRONMENT 0.01 to 10 kGy per year
single event upsets

ASIC for LHC timing distribution

- TTCrx: 40 MHz opto-receiver for high precision clock distribution
  - 1 to 30,000 optical fan-out
  - 100 ps resolution
  - low jitter
- DMILL technology
  - rad-hard
  - 0.8 µm BiCMOS
  - ~ 5x5 mm2



Cerenkov LIGHT IMAGER in LHCb



VACUUM PHOTOTUBE
Si PIXEL ASSEMBLY
USED as ANODE

CERN + DEP, Roden NL

MULTITUDE of SENSORS

MOMENTUM MEASUREMENT via TRACKING
'EMPTY' INNER REGION : GAS or THIN
SILICON also : CERENKOV RINGS

MUONS are MESSENGER PARTICLES
TRAVERSE THICK LAYERS
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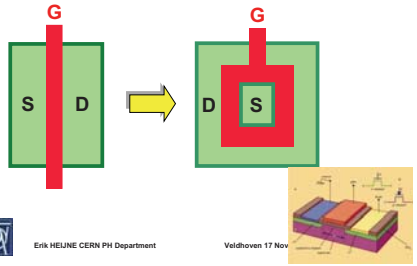
TOTAL ENERGY MEASUREMENT
ELECTROMAGNETIC SHOWERS
HADRONIC SHOWERS
LIGHT COLLECTED from HEAVY CRYSTALS
CHARGE in LIQUID ARGON

+ Design trick



High Speed Serializer

LHC OPTICAL DATA LINK

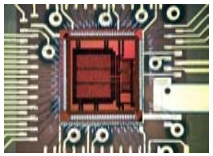
Gigabit Optical Link (GOL)
0.8 and 1.60 Gb/s optical link

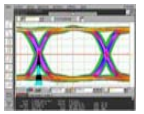
Unidirectional

< 300 mW

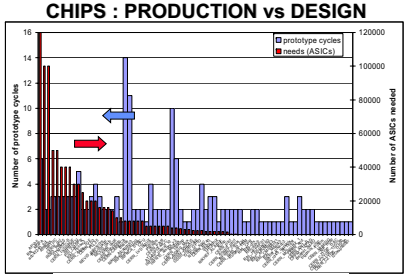
G-Link and Gigabit Ethernet protocol

Redundant logic

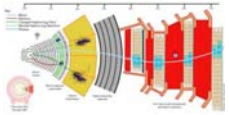




CHIPS : PRODUCTION vs DESIGN



CMS SEQUENCE of SENSOR DEVICES



Solenoid:
Length: 13 m
Diameter: 5.9 m
Superconducting coil (NbTi)
Current: 20 kA
Operating temperature: 4.4 K (-269 C)
Magnetic Field: 4 Tesla
x 100 000 Earth field
Stored energy: 2.7 GJ

Tracker: Silicon Pixel and Silicon Microstrip
Measurement of momentum of electrically charged particles
Reconstruction of vertices (interaction points + particle decays)

Electromagnetic Calorimeter: Crystals of Lead Tungstate (PbWO4)
Measurement of the energy of: electrons/positrons and photons

Endcap Preshower: Silicon Strip Sensors
Measurement of the transverse profile of electromagnetic showers

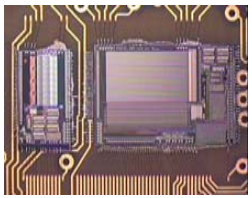
Hadronic Calorimeter: Plastic Scintillators
identification and measurement of quarks, gluons and neutrinos
Measurement of the energy and direction of jets
Measurement of missing transverse energy

Muon chambers: Drift Tubes and Cathode Strip Chambers
detection of muons

Front end design example: Calo preshower

PACE 32 channels
low noise
12 bit dynamic range
192 deep
analog memory
(on separate chip)
serial analog read-out

CMS
Aspell, Bloch, et al.



SILICON as 'BUBBLE CHAMBER'

SILICON DETECTORS ALLOW PRECISE TRACKING

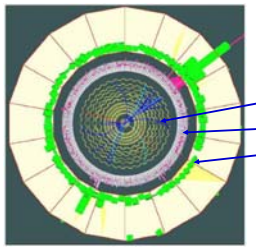
MICROSCOPIC SEGMENTATION with LITHOGRAPHY

HIGH RESISTIVITY SILICON ~5 kΩcm DIODES
FULLY DEPLETED at < 100V

ENERGY LOSS in 300 µm SILICON RESULTS in
SIGNAL ~ 20 000 e-h pairs
LINEAR with THICKNESS for 'M.I.P.'
minimum ionizing particles ≥ 0.2 GeV

SEGMENTATION POSSIBLE THANKS TO CHIP READOUT

CMS DISPLAY



LAYERED 2D PROJECTION

TRACKER

EM CALORIMETER

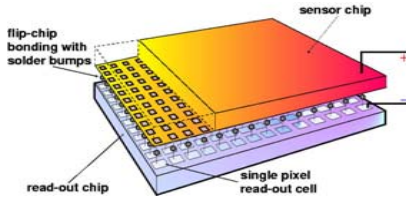
HADON CALORIMETER

PRELIMINARY

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

ATLAS CALORIMETER

Hybrid Pixel Detector

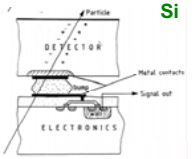


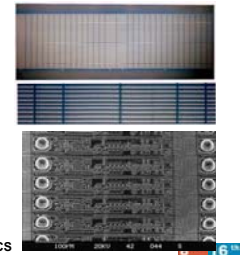
HYBRID Si PIXEL SENSOR 1991

CERN : CAMPBELL, HEIJNE

SENSOR MATRIX TRUE 2 - D

Si





BUMPS
+
READOUT ELECTRONICS

INTERMEZZO

POCKET-SIZE SILICON 'BUBBLE CHAMBER'

THANKS TO MICROELECTRONICS

PORTABLE MEDIPIX2 USB

MEDIPIX2 MUROS2 NIKHEF vs USB PRAGUE

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

REDUCTION in
SIZE
CABLES
POWER

CAPABILITY in SPEE not yet equal

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

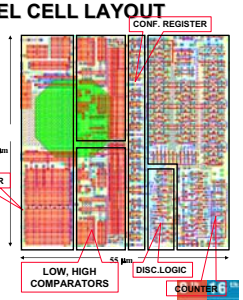
http://medipix.web.cern.ch/MEDIPIX/

SPOKESMAN Michael CAMPBELL
Deputy Jan VISSCHERS

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.



MEDIPIX2 USB CLOSE-UP PRAGUE-CERN

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

BIAS VOLTAGE up to 100V
Generated in the USB

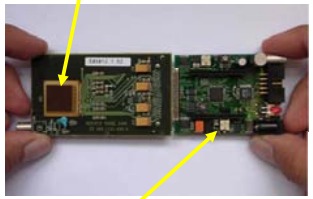
FILTERING FAR TOO BIG NOW
USE SMALLER CARD & COMPONENTS

COMPLETE USB PROCESSOR
in NICE BOX, serial 0003

STANDARD USB CABLE to NOTEBOOI

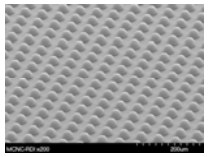
MEDIPIX2 USB OPEN PRAGUE

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



COMPLETE USB PROCESSOR
NO BOX

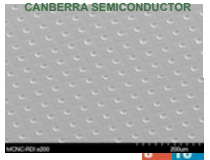
BUMP BONDING Medipix2



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

MINIATURE DETECTOR 'MEDIPIX'

USES INDUSTRIAL PROGRESS in MINIATURIZATION

FPGA, USB, ..

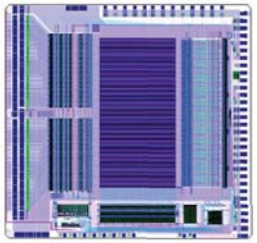
Front-end design examples

APV25: 128 channels
low noise
8 bit dynamic range
192 deep analog memory
serial analog read-out

0.25 µm CMOS, 1P, 3M

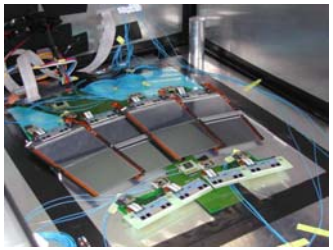
~120,000 chips in CMS Tracker

"Special" design rules for radiation tolerance



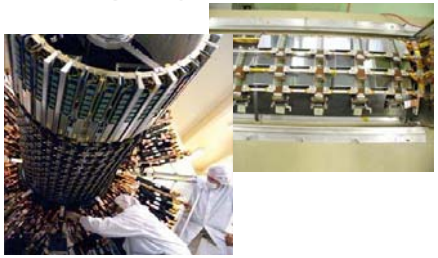
APV25-S1

CMS SILICON TRACKER

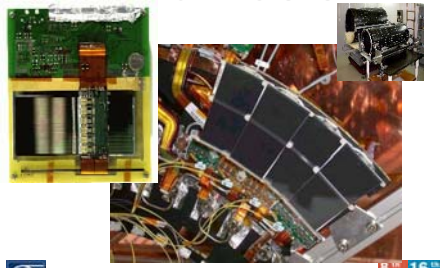


'FORWARD' Si STRIP MODULES

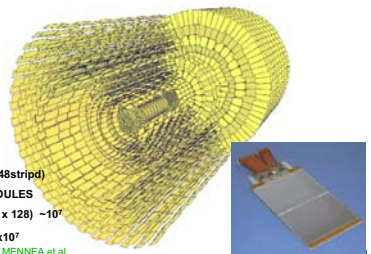
Si TRACKER : BARREL



Si TRACKER MODULES



CMS SILICON TRACKER



16540 (15148stripd)
STRIP MODULES
(4-6 CHIPS x 128) ~10⁷

PIXELS ~ 4x10⁷

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

CMS Tracker read-out in detail

~ 120,000 FE chips with 128 channels each

Total Power budget: 3 mW/channel

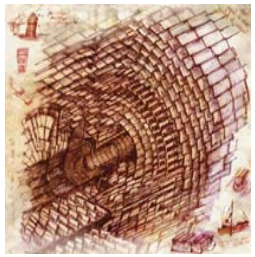
~50,000 analog optical links

Synchronous 40 MHz clock distribution to all channels with 1 ns skew adjustment

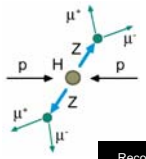
External digitization, after zero suppression data flow needs ~500 digital links @ 4 Gb/sec

Control system includes ~20,000 special purpose ASICs organized in token-ring like architecture

All ASICs designed with 0.25 µm CMOS

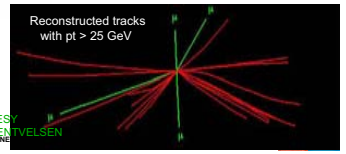


EVENT with HIGGS PARTICLE



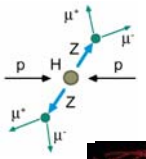
Higgs→Z^0Z^0→ $\mu^+\mu^-\,\mu^+\mu^-$

VERY CLEAR EVENT (THE 4 µ)
BUT EXTREMELY RARE



COURTESY
STAN BENTVELSEN

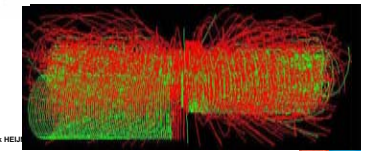
EVENT with HIGGS PARTICLE



Higgs→Z^0Z^0→ $\mu^+\mu^-\,\mu^+\mu^-$

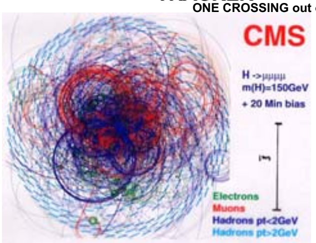
VERY CLEAR EVENT (THE 4 µ)
BUT EXTREMELY RARE

NOT EASY TO FIND
THIS IS HOW IT LOOKS EXPERIMENTALLY
ALWAYS LARGE BACKROUND



SAME SIMULATED in CMS Si TRACKER

ONE CROSSING out of 4×10^7 each sec



DATA ACQUISITION SCHEME

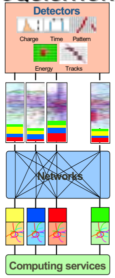
40 MHz COLLISION RATE

100 kHz LEVEL-1 TRIGGER

1 Terabit/s (50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

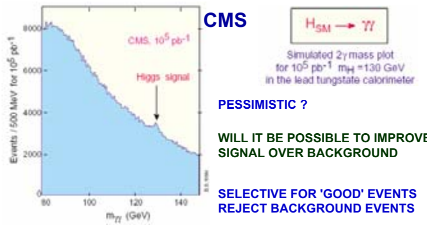
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

SIGNAL and BACKGROUND

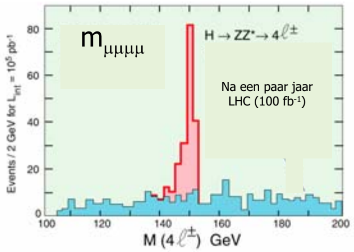


PESSIMISTIC ?

WILL IT BE POSSIBLE TO IMPROVE SIGNAL OVER BACKGROUND

SELECTIVE FOR 'GOOD' EVENTS
REJECT BACKGROUND EVENTS

SEEING THE HIGGS PARTICLE



SIMULATION for ONE POSSIBILITY

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

USE A VARIETY of POSITION SENSITIVE DETECTORS

SIGNAL PROCESSING, DATA TRANSMISSION, INFORMATION EXTRACTION

THE END

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 ~100ns timescale

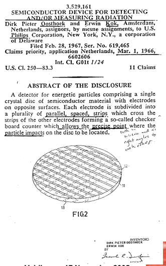
BOL

Si DETECTORS are the PRIDE OF BOL
FIRST DOUBLE-SIDED, SEGMENTED STRIP DETECTOR

NEED SOPHISTICATED ELECTRONICS

PATENT DOUBLE-SIDED Si STRIP DETECTOR

OOSTHOEK & KOK
1967 FILED in USA



3,529,161
SEMICONDUCTOR DEVICE FOR DETECTING AND/OR MEASURING RADIATION
Dirk Pieter Oosthoek and Erwin Kok, Amsterdam, Netherlands, assignors, by mesne assignments, to U.S. Philips Corporation, New York, N.Y., a corporation of Delaware
Filed Feb. 28, 1967, Ser. No. 619,465
Claims priority, application Netherlands, Mar. 1, 1966, 6602606
Int. Cl. G01t 1/24
U.S. Cl. 250—83.3 11 Claims

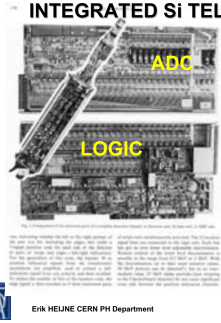
ABSTRACT OF THE DISCLOSURE

A detector for energetic particles comprising a single crystal disc of semiconductor material with electrodes on opposite surfaces. Each electrode is subdivided into a plurality of parallel, spaced, strips which cross the strips of the other electrodes forming a so-called checker board counter which allows the precise point where the particle impacts on the disc to be located.

FIG2

INVENTORS
DIRK PIETER OOSTHOEK
ERWIN KOK
BY

INTEGRATED Si TELESCOPE



NIM 92 (1971)
OBERSKI et al.

IKO BOL 1968-72

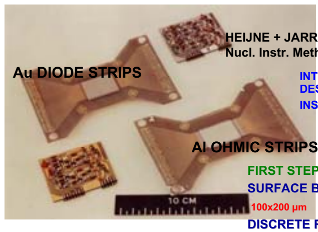
STATE of ART TECHNOLOGIES

2D Si DETECTORS

UNIQUE COLLABORATION
with INDUSTRY

INTEGRATED DESIGN
SENSORS, READOUT ELECTRONICS
MECHANICS & COOLING
OFF-LINE PROCESSING

CERN MICROSTRIP DETECTORS



HEIJNE + JARRON et al.
Nucl. Instr. Meth 178 (1980) 331

INTEGRATED DESIGN
INSPIRED BY IKO-NL

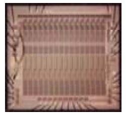
FIRST STEP : JAN - JUNE 1980
SURFACE BARRIER STRIPS
100x200 μm
DISCRETE READOUT
(FAST,DENSE)

RECTANGULAR SHAPE: UNUSUAL but ESSENTIAL

HERMETIC PAD DETECTORS UA2

16 CHANNELS
COLLABORATION
IMEC LEUVEN

~5 mm THICK CILINDER
ONLY POSSIBLE with "AMPLEX" CHIP DESIGN Pierre Jarron



1986 - 1988