

Silicon Detectors for Particle Physics

9. August 2012

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Outline

Different Cameras

Silicon Detectors

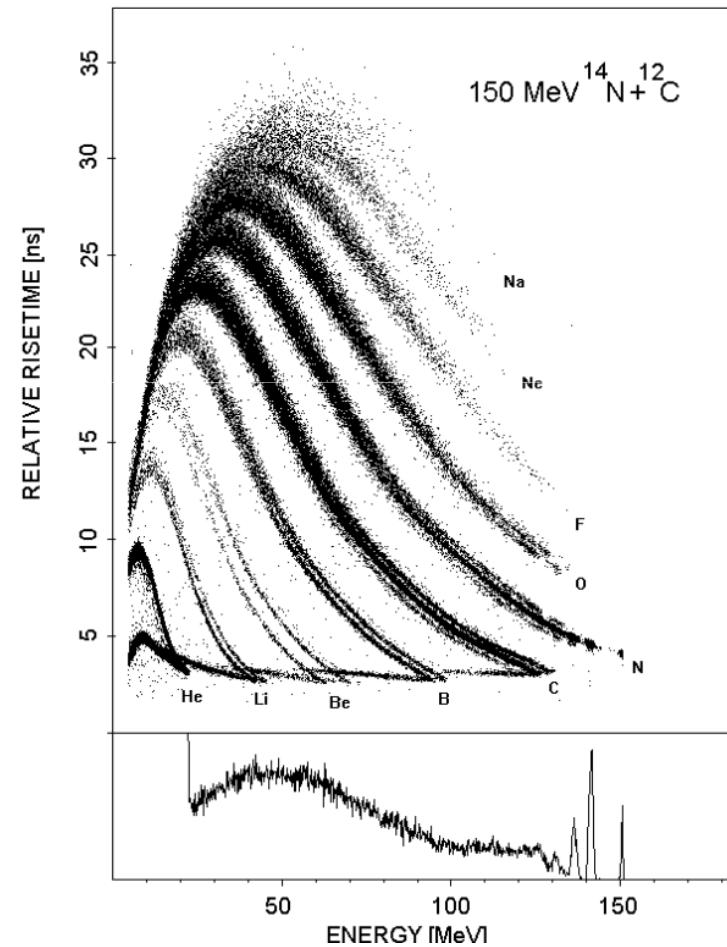
Taking Pictures in Particle Physics

Different Cameras



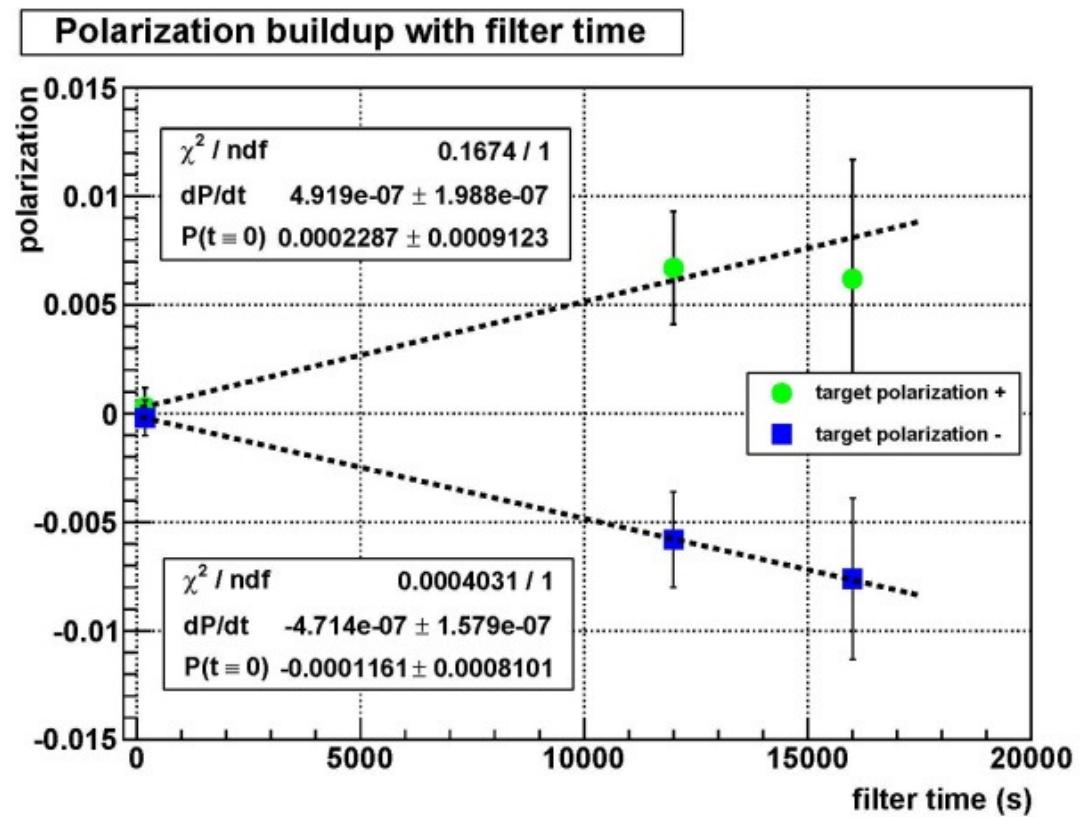
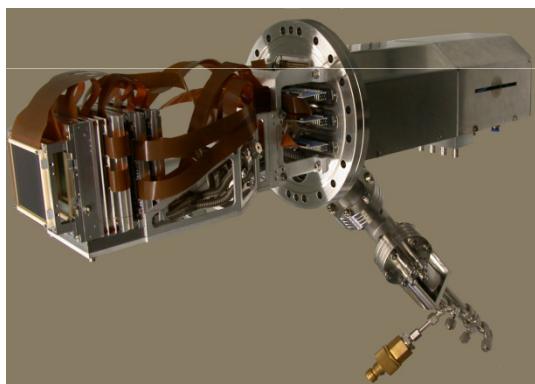
Different Cameras

Surface Barrier ,Single-Pixel Camera'



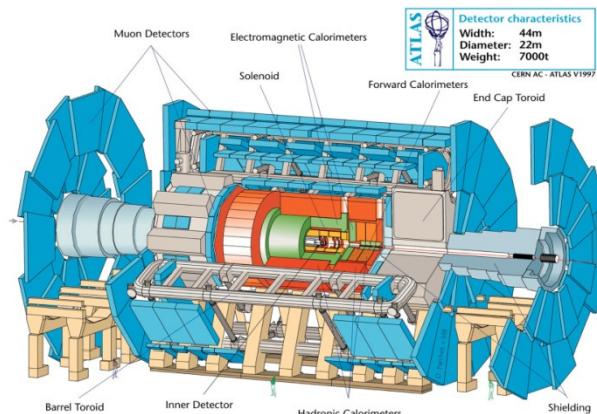
Different Cameras

Silicon Tracking Telescope ,Camera‘

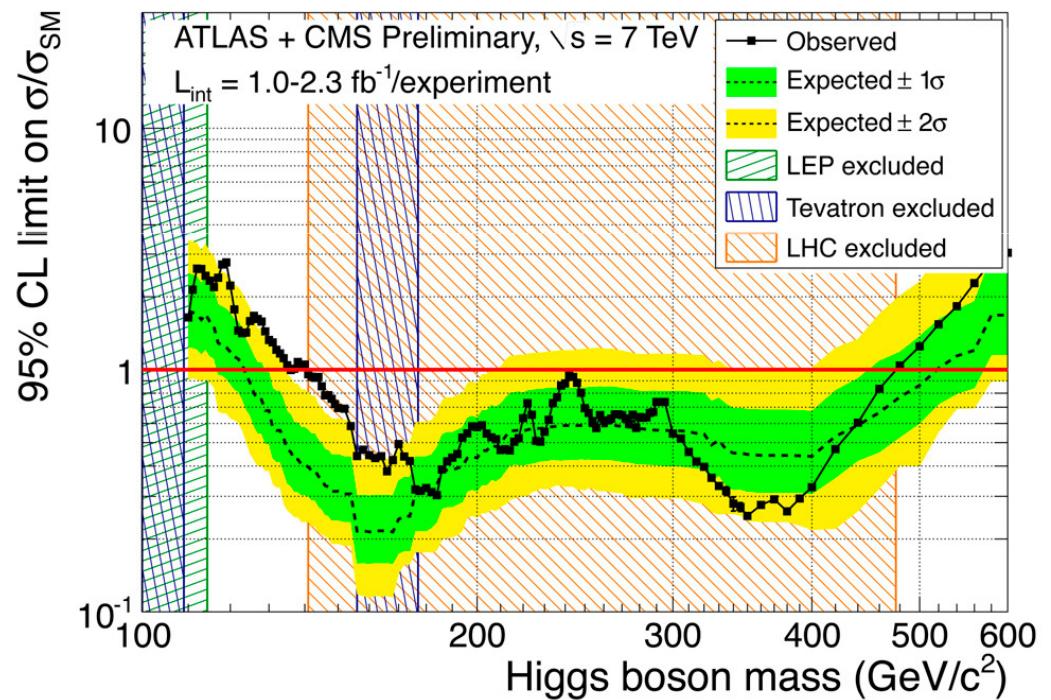
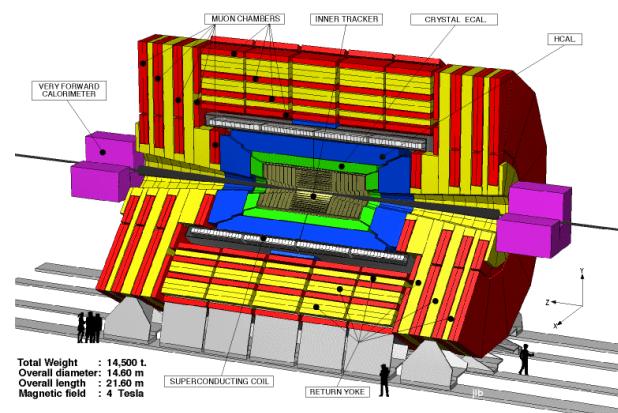


Different Cameras

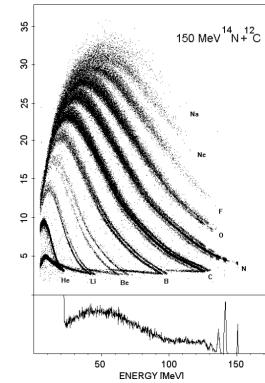
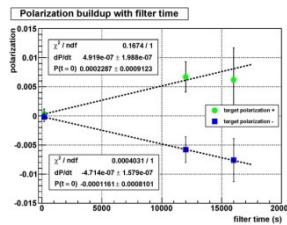
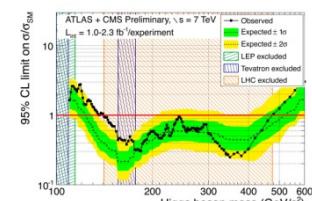
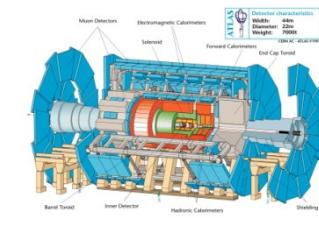
ATLAS 'Camera'



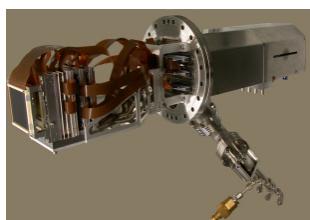
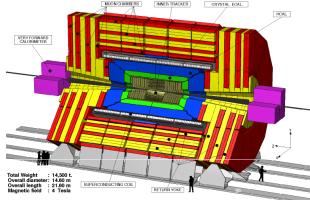
CMS 'Camera'



What do all these cameras have in common?



- They are expensive for the photographer.
- The photographer is proud to have them.
- The intuition which picture to take is not implemented.

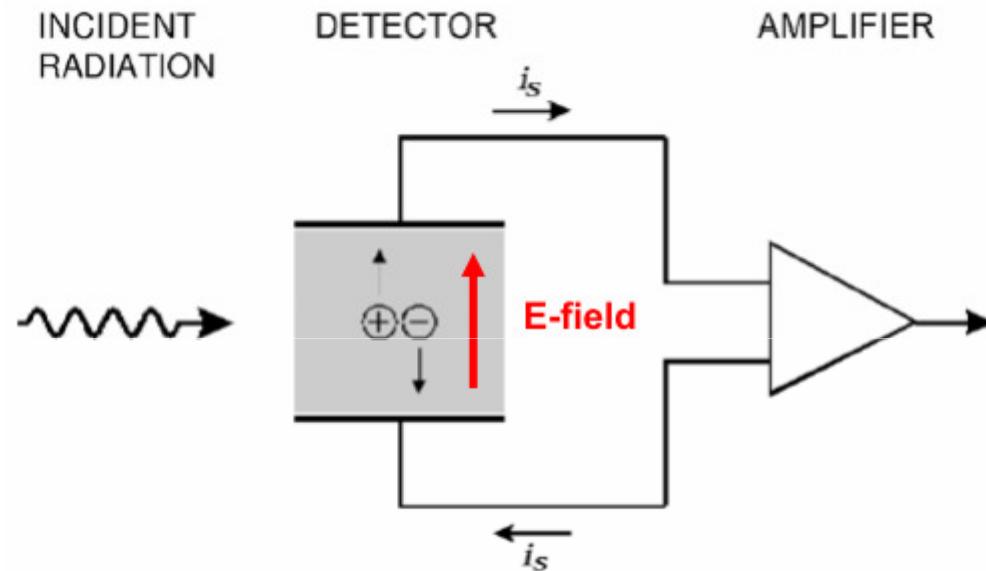


and seriously

- They all have silicon sensors to take the pictures.
- They all have the same underlying principle



The Principle



A Brief History of ‚Silicon Cameras‘

- 1951 First detectors with germanium pn-diodes (McKay)
- 1959 Gold Surface Barrier Si-Diode
J.M. McKenzie and D.A. Bromley, Bull. Am. Phys. Soc. 4 (1959) 422
- 1960 Working samples of p-i-n detectors (E.M. Pell)
- 1961 Lithium drifted thick detectors (J.H. Elliot, NIM 12 (1961) 60)
- 1964 Use of semiconductor detectors in nuclear physics (G.T. Ewan, A.J. Tavendale)
- 1980 Planar technology (J. Kemmer, NIM 169 (1980) and NIM 226 (1984) 89)**
- 1980-86 CERN NA11 and NA32 measure charm meson lifetimes with planar Si-detectors
- > 1990 Europe: CERN: ALEPH, DELPHI, L3, OPAL
DESY: H1, HERMES, HERA-B, ZEUS.
USA: FermiLab: CDF and D0
- > 2000 Europe: CERN ATLAS, ALICE, CMS, LHC-b.
USA: SLAC Babar
Japan: KEK BELLE
...

Silicon Strip Detectors: The Birth

Fixed target experiment at CERN with a planar diode.
First of planar process developed for chip industry.

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502. © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

Fachbereich Physik der Technischen Universität München, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof Dr H-J Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than $1 \text{ nA cm}^{-2}/100 \mu\text{m}$ at room temperature. Best values for the energy resolution were 10.0 keV for the 5486 MeV alphas of ^{241}Am at 22°C using $5 \times 5 \text{ mm}^2$ detector chips.

The birth: NA11 at CERN

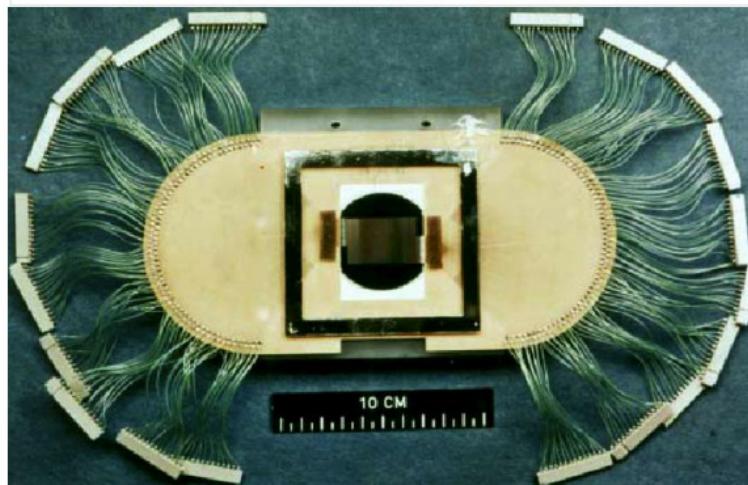
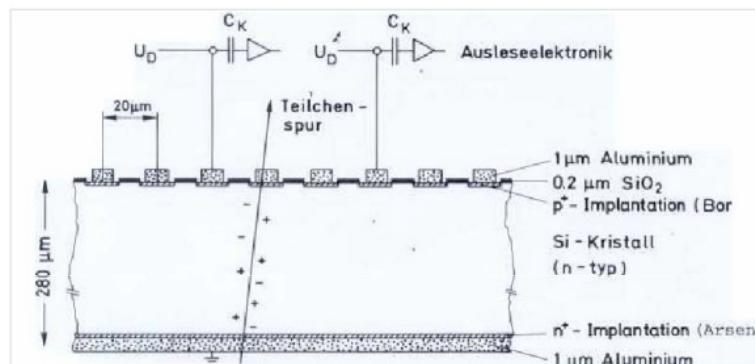
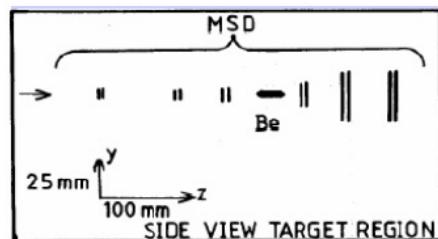
The aim: Measure lifetime of charm quarks (decay length $30\mu\text{m}$)

1981: first detectors in beam:

- 24 x 36 mm, 1200 strips
- 20 μm strip pitch
- 60 μm readout pitch
- area Si telescope: 0.01 m^2

→ 5.4 μm accuracy
 → 100 % efficiency

- build at the MPI-workshop a high resolution vertex detector (6 beam + 6 vertex detectors) with a total of 2000 channels running in early 1982

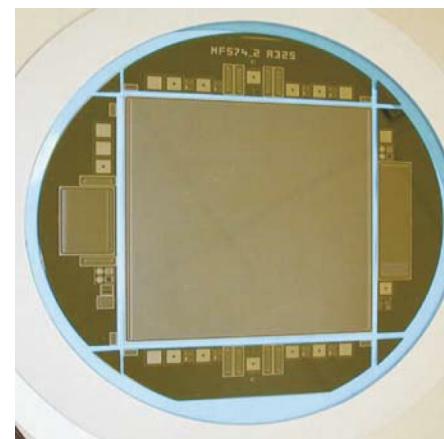


Silicon Strip Detectors: The Fabrication

From sand ...



...to silicon detectors.

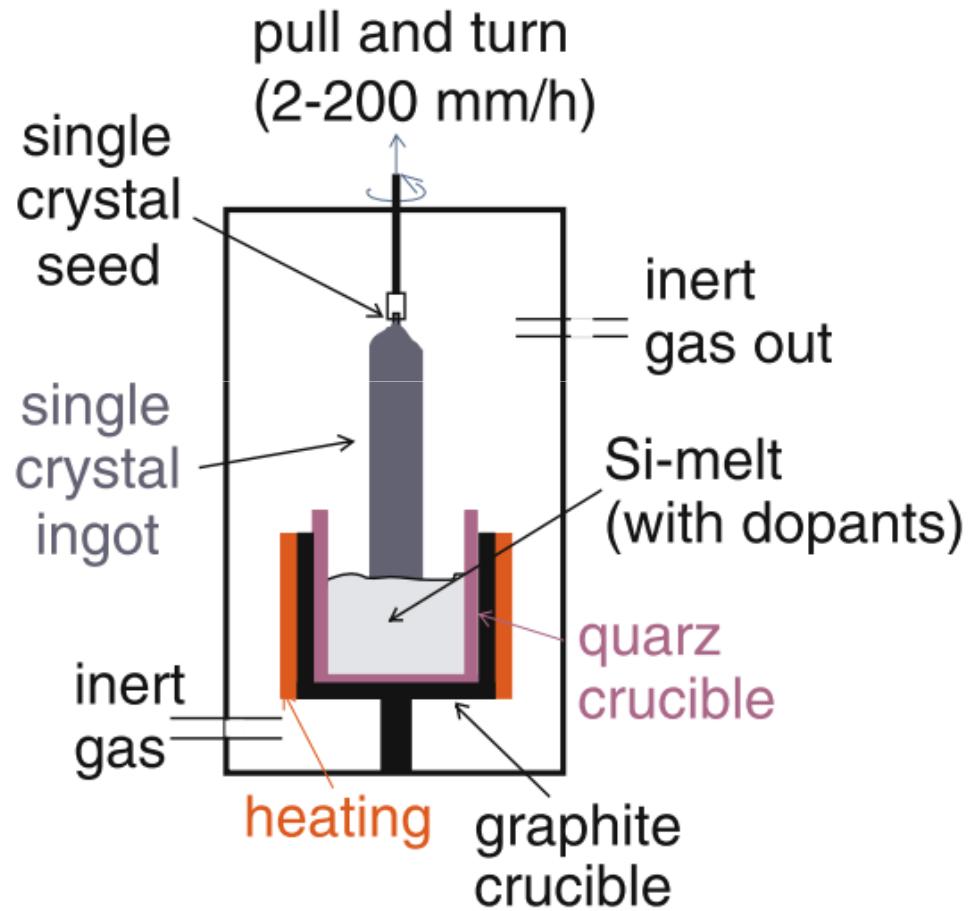


The Fabrication: Polycrystals

- sand (SiO_2) is heated in a furnace to 1650°C and deoxidated to gaseous SiO.
- SiO reacts to 99 % pure raw silicon.
- raw silicon is treated chemically to get 100 % pure polycrystalline silicon



The Fabrication: Monocrystals



The Fabrication: Planar Process

Polishing and cleaning

Oxidation at 1300 K

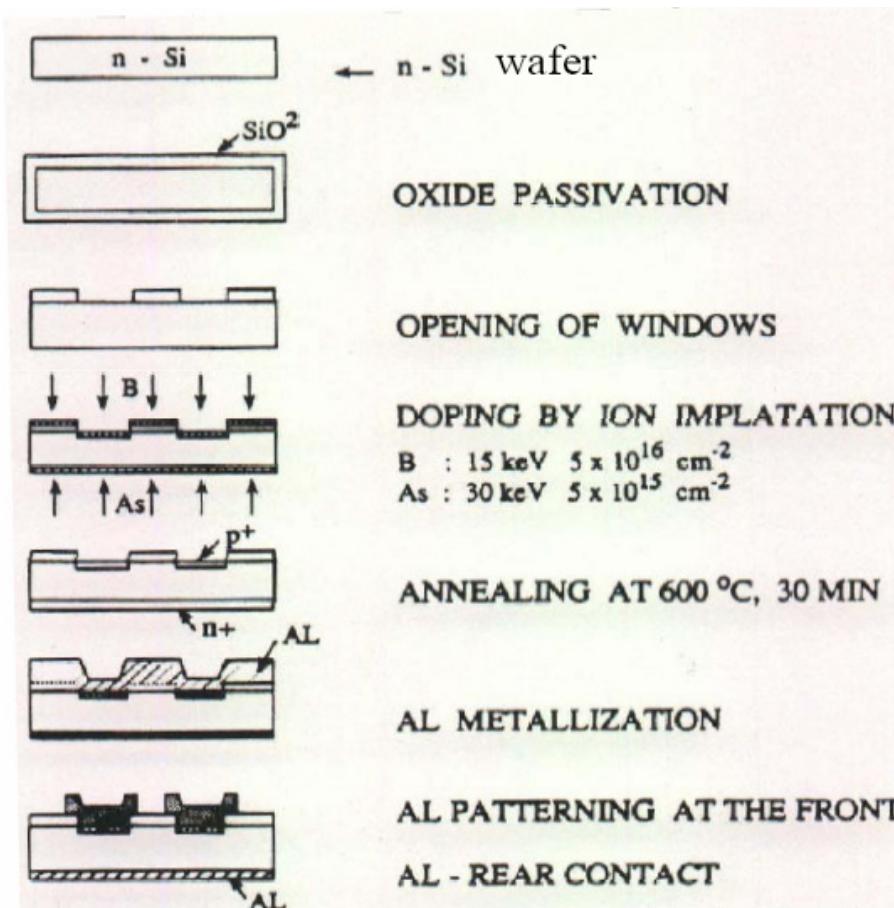
Deposition of photosensitive polymer, UV illumination

Creation of p-n junction via implantation/diffusion

Annealing: implanted ions occupy lattice sites

Deposition of Al and

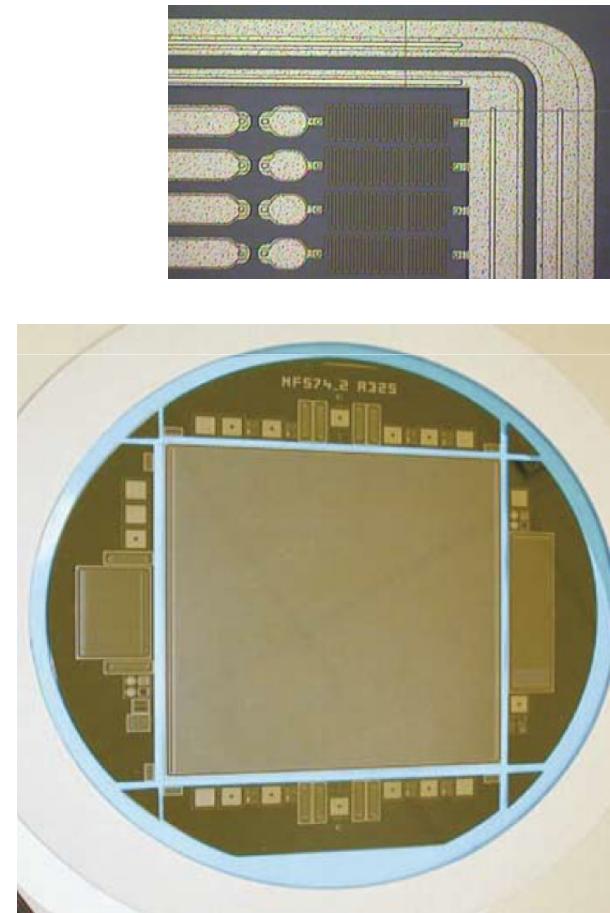
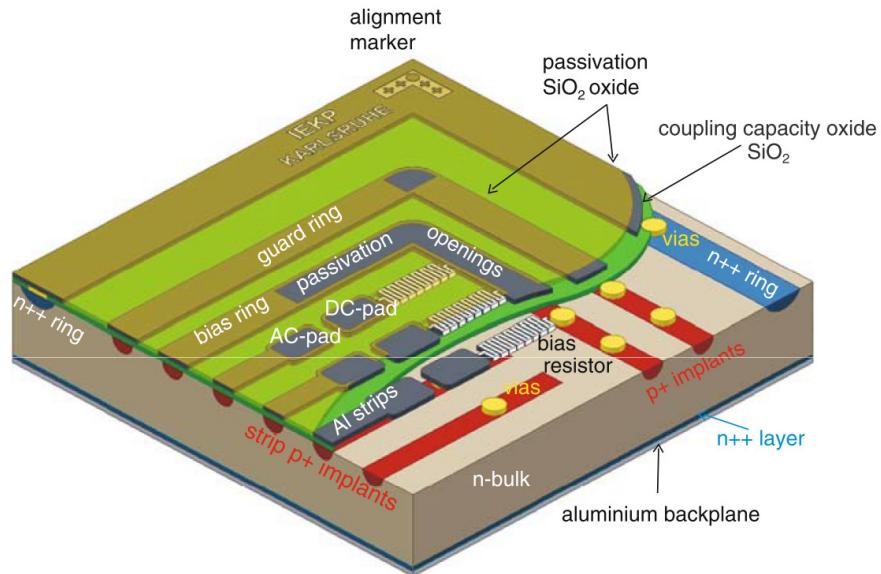
patterning for electric contacts



Silicon Detectors: Fabrication

- Use very pure material
 - High resistivity
 - *Low bias to deplete device*
 - Easy of operation, away from breakdown, charge spreading for better position resolution
 - Low defect concentration
 - *No extra current sources*
 - *No trapping of charge carriers*
- Planar fabrication techniques
 - Make p-i-n diode
 - pattern of implants define type of detector (pixel/strip)
 - extra guard rings used to control surface leakage currents
 - metallisation structure effects E-field mag \Rightarrow limits max bias

Silicon Strip Detector



6 inch wafer

Silicon Detectors: LEP@CERN and SLAC

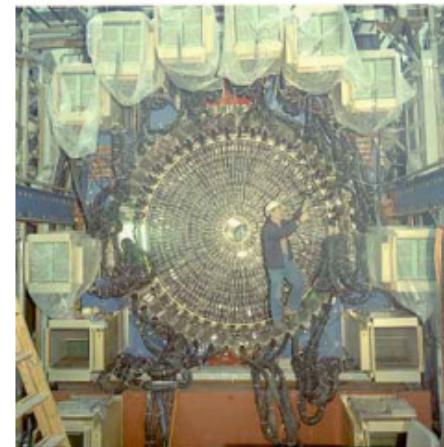
Experiments:

- LEP Detectors at CERN
 - SLAC Linear Collider (Mark II experiment)
-
- Minimize the mass inside tracking volume
 - Readout chips at end of ladders
 - Minimize the mass between interaction point and detectors
 - Minimize the distance between interaction point and the detectors

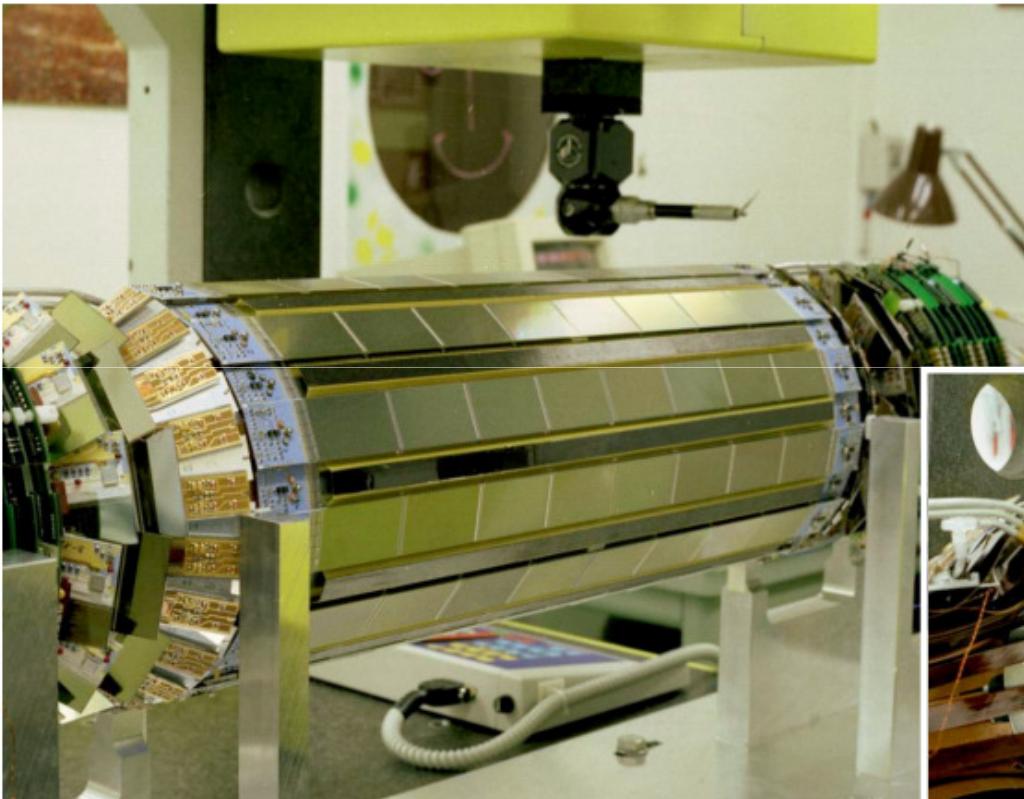
DELPHI



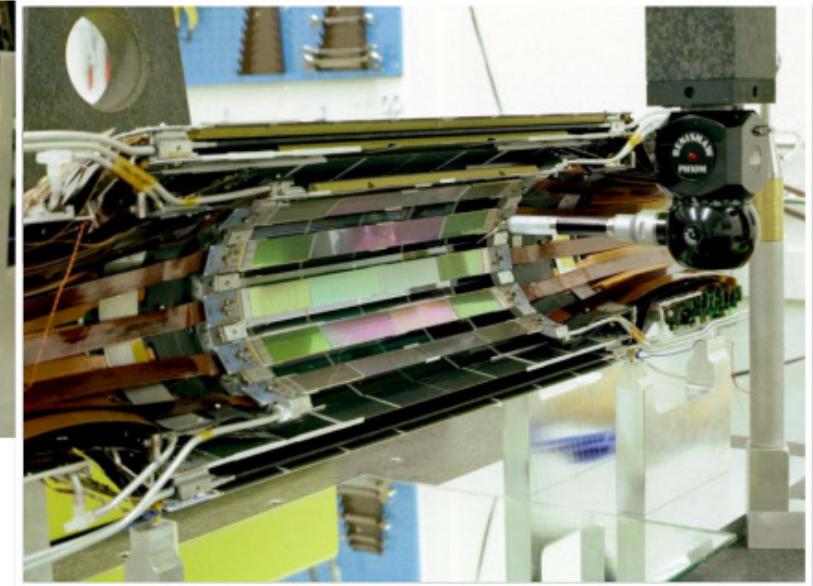
Mark II



Silicon Detectors: DELPHI@LEP (CERN)



- 2 silicon layers, 40cm long, inner radius 7.8 cm, outer radius 12cm
- 300µm DSSDs with double metal readout



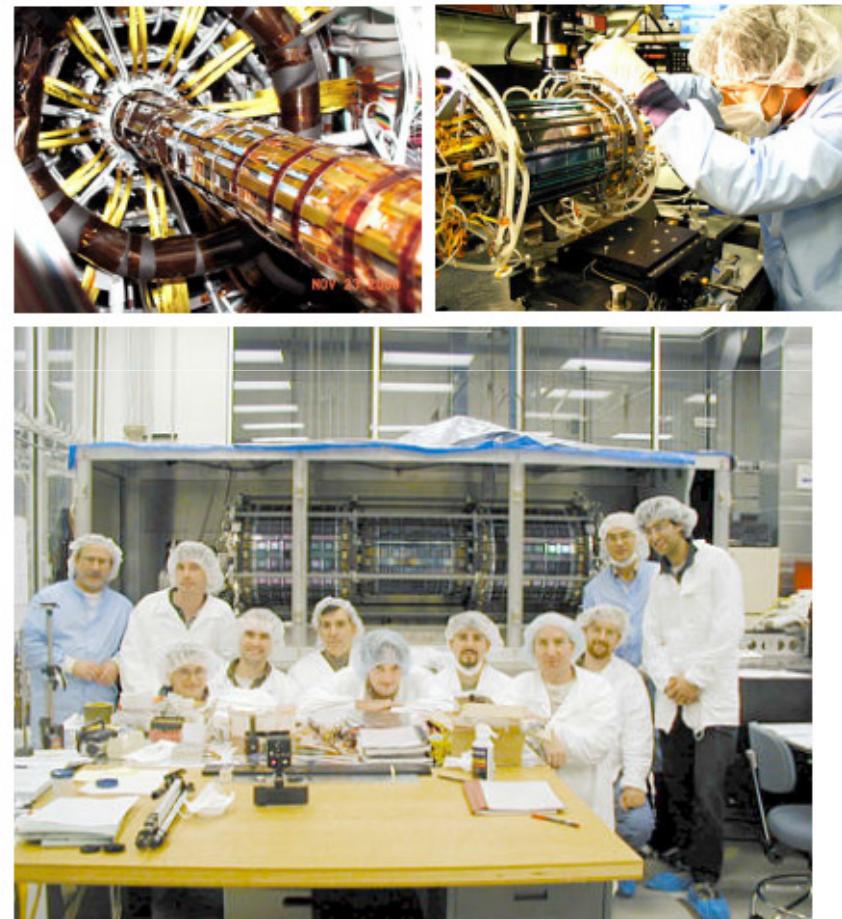
Silicon Detectors: CDF@Tevatron (FermiLab)

Collider Detector at Fermilab (CDF) is one of the two Experiments at the 2x1TeV Tevatron

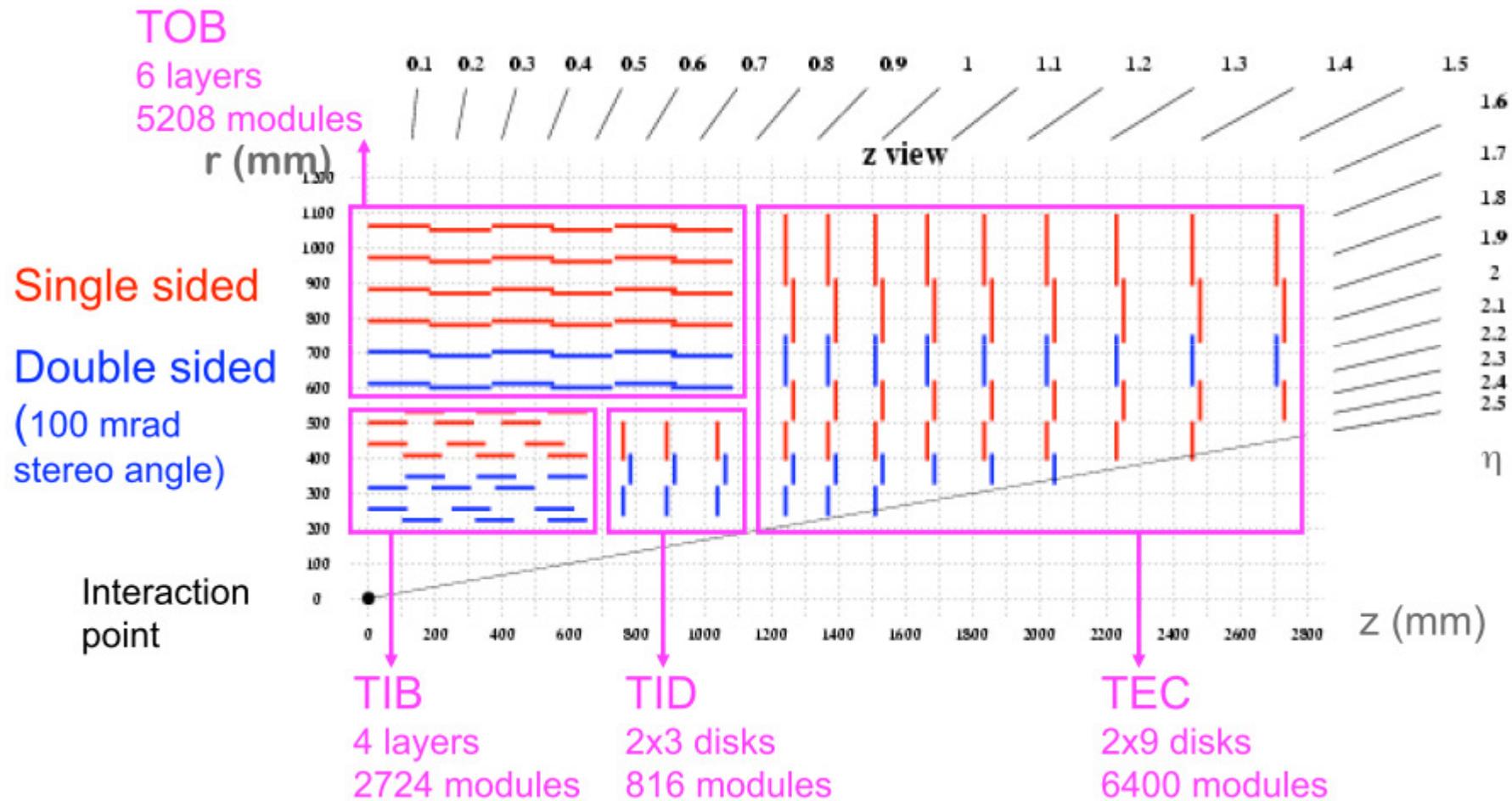
- Discovery of top-quark (1995)

Tracker:

- Barrel only (no endcaps)
- Different Silicon Layers:
 - L00 (SSSD, $r \sim 1.5$ cm, $l=94$ cm)
 - SVX ($r = 5\text{-}10$ cm)
 - ISL (DSSD, $r = 20\text{-}29$ cm)
- Total active area: approx. 10 m²

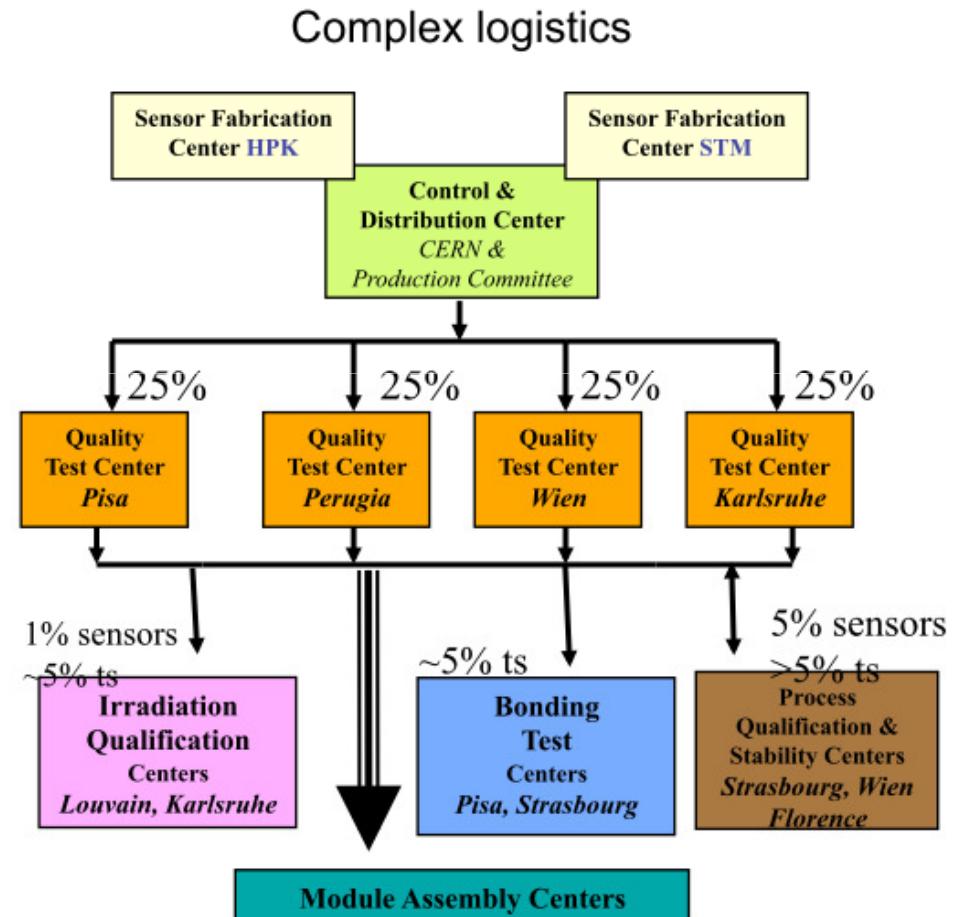


Silicon Detectors: CMS Tracker@LHC (CERN)

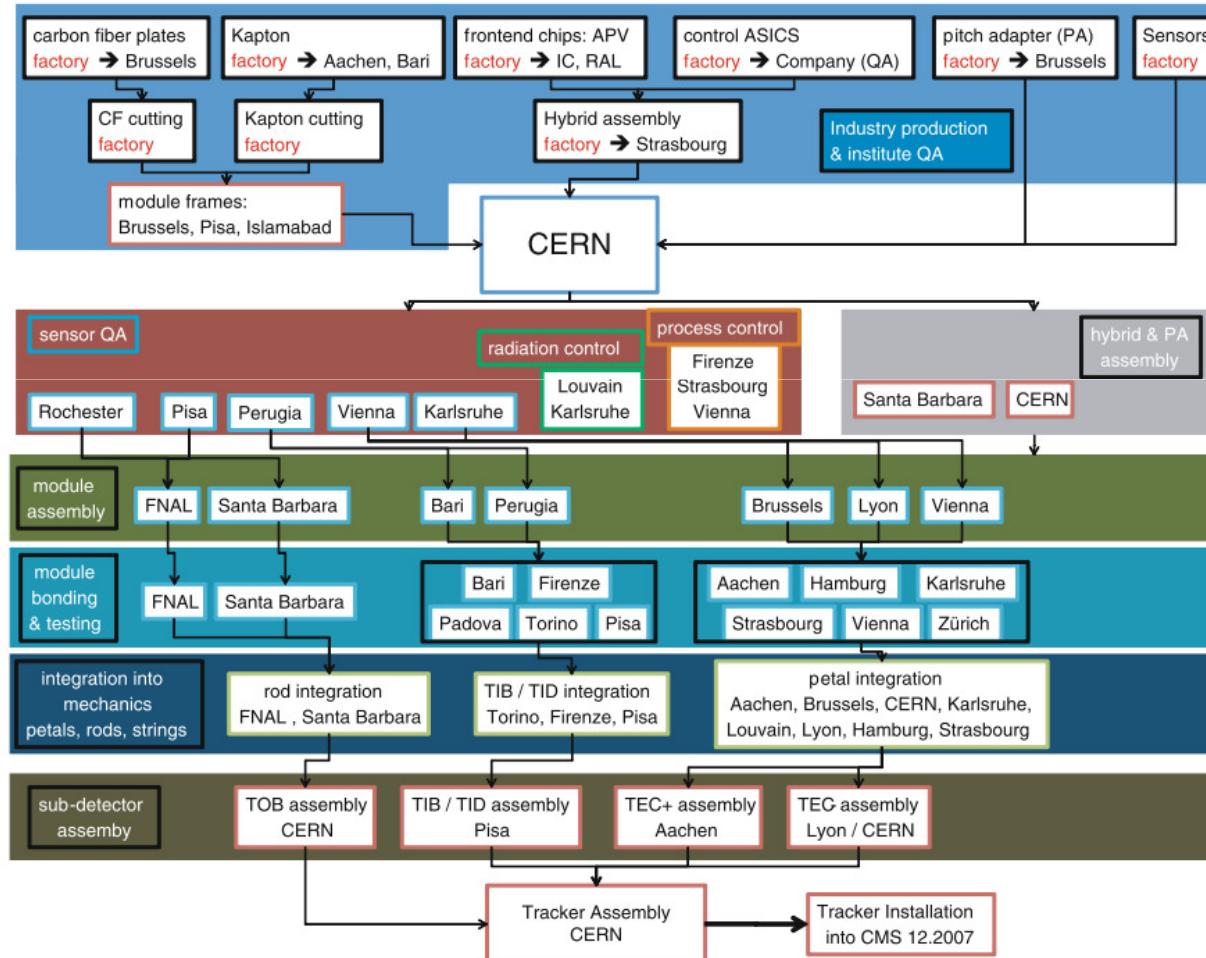


CMS Tracker: Silicon Sensors

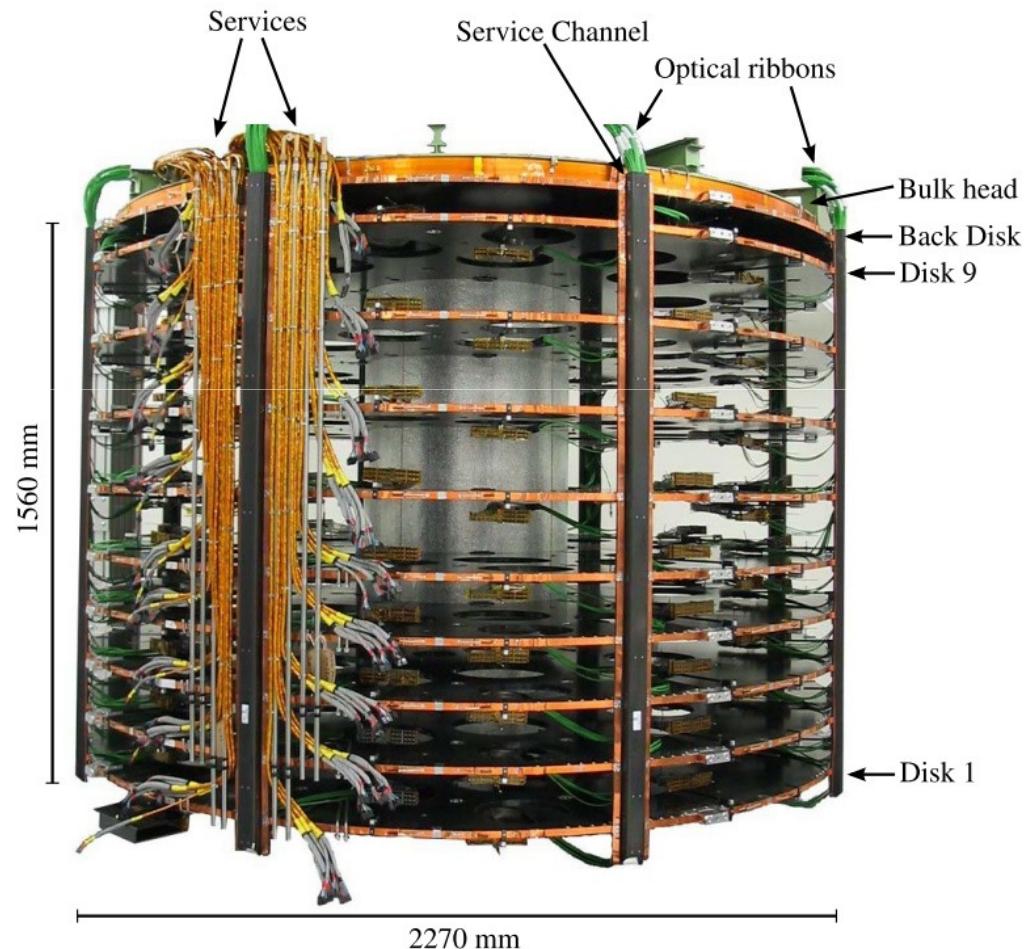
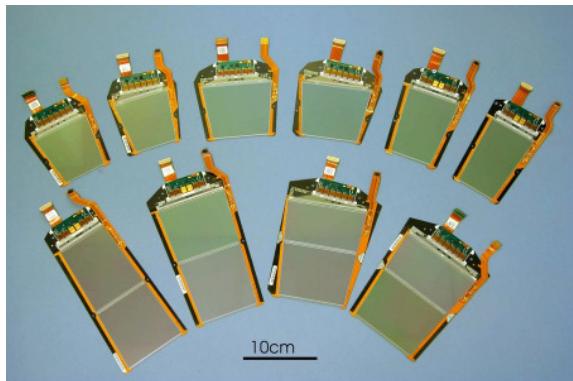
- Two producers:
 - Hamamatsu Photonics (Japan)
 - ST Microelectronics (Italy)
- Four main Test centers
 - Supported by smaller tests in different locations
 - Irradiation
 - Bonding tests
 - Process Qualification & Longterm stability



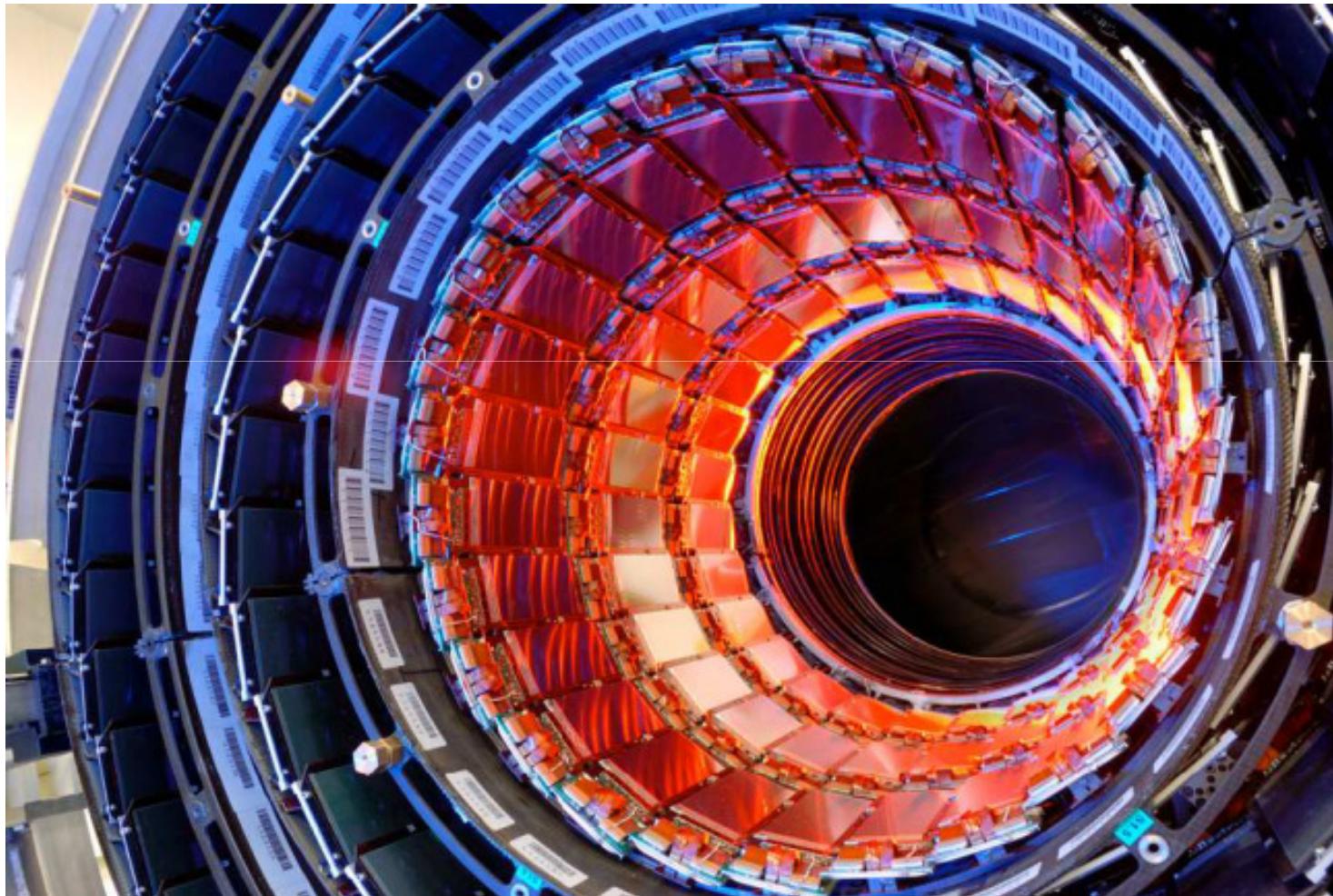
CMS Tracker: Logistics



CMS Tracker

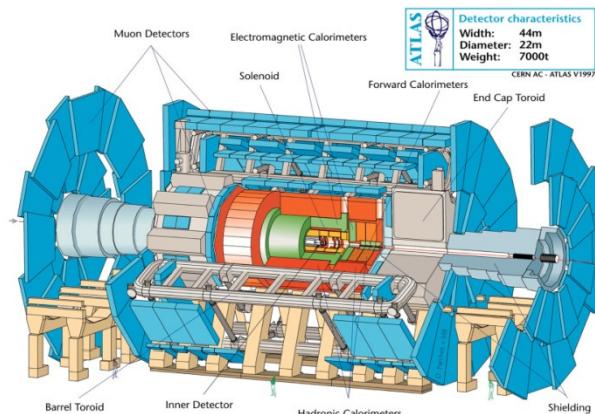


CMS Tracker as a Camera ...

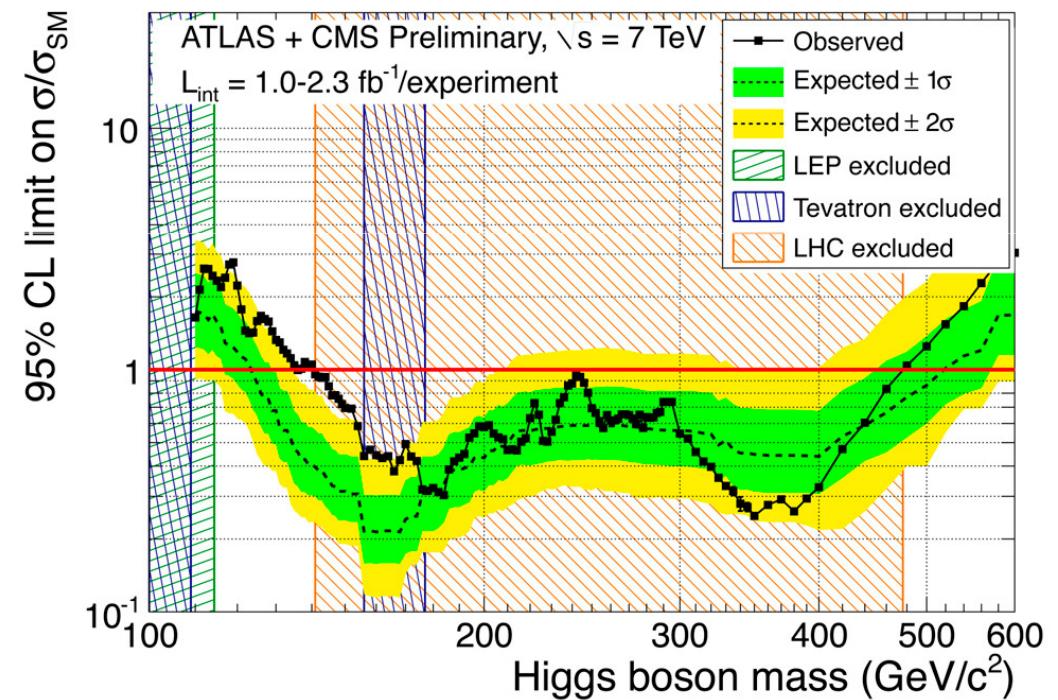
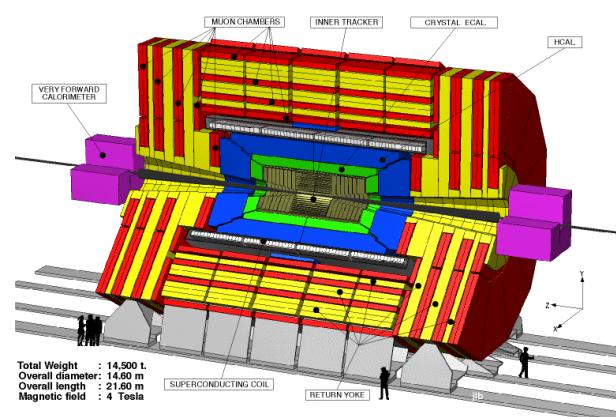


... and the picture:

ATLAS , Camera'

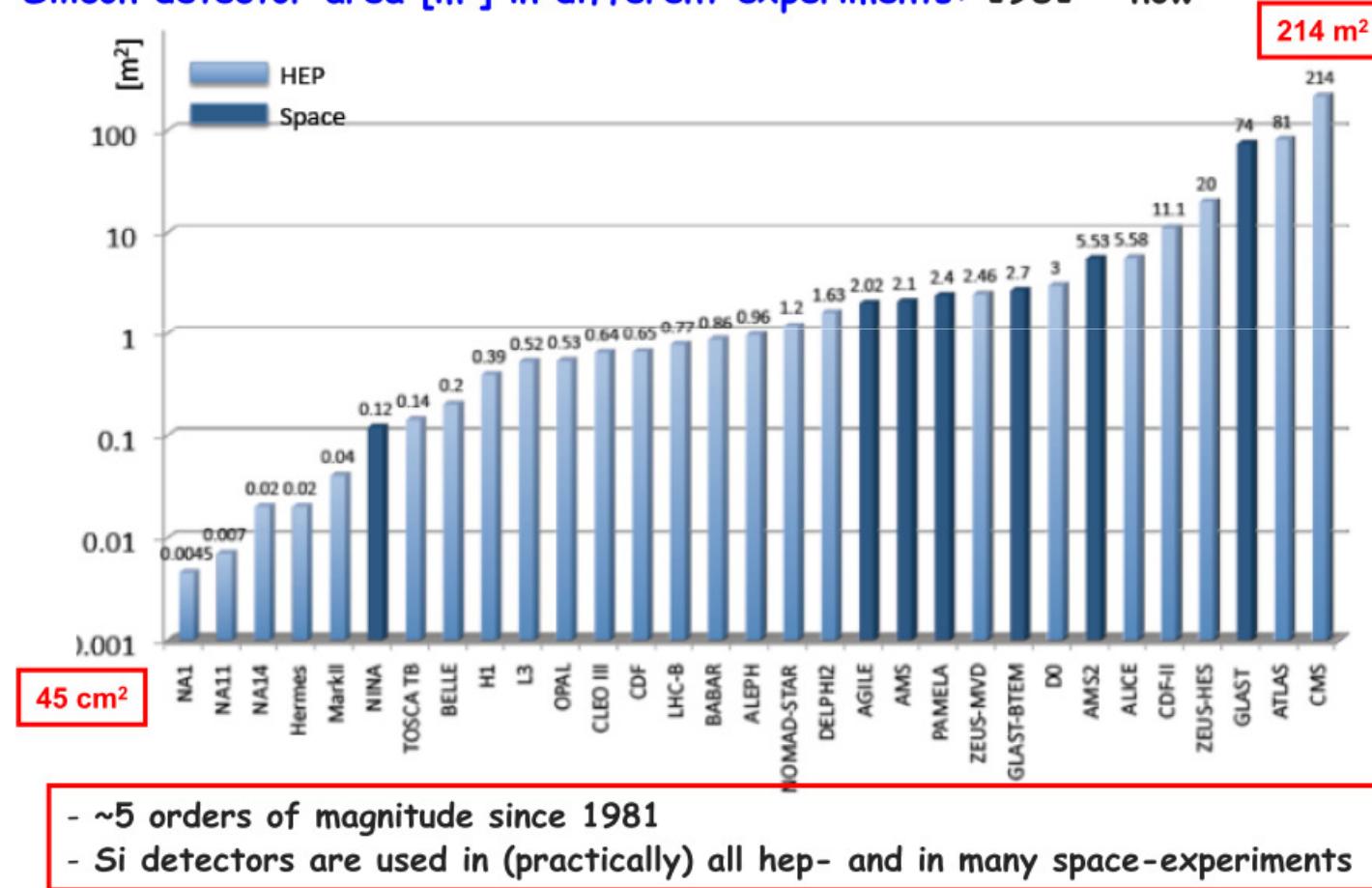


CMS , Camera'

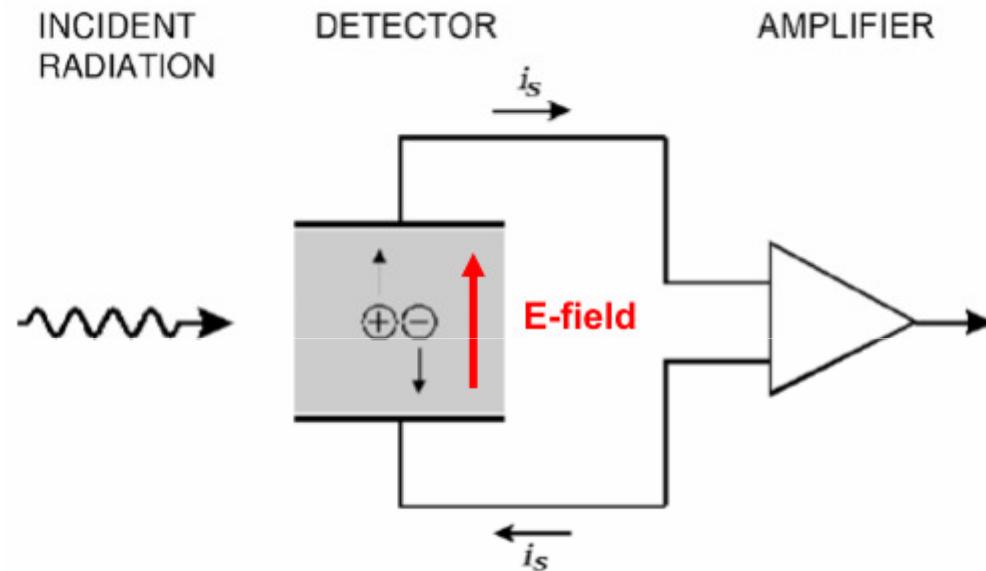


Silicon Detectors: Development in Size

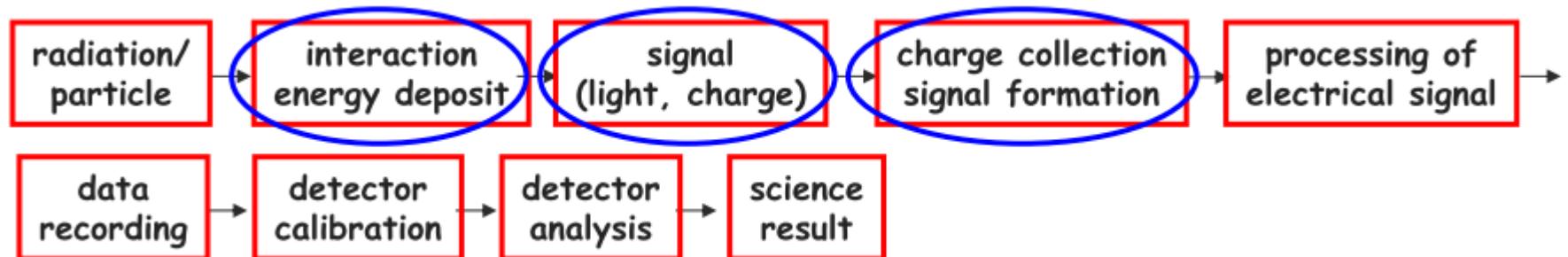
Silicon detector area [m^2] in different experiments: 1981 - now



The Principle



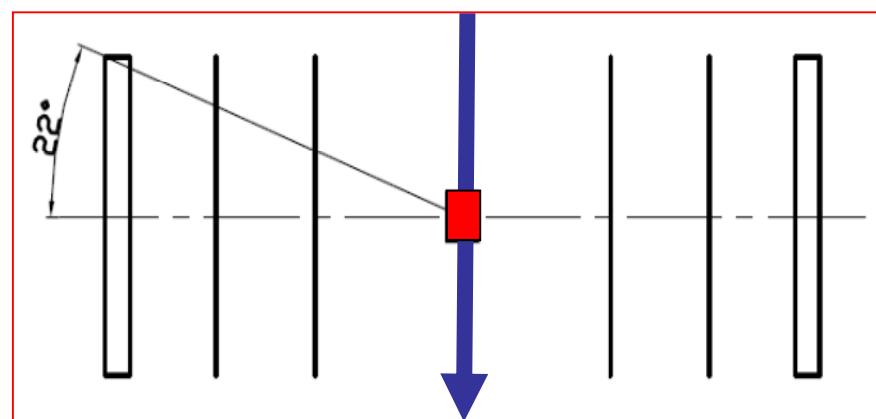
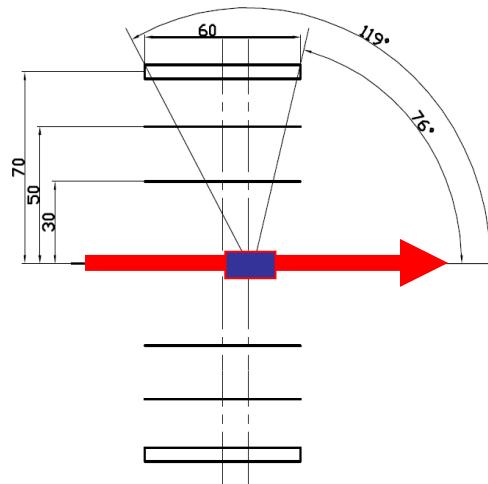
How to take a picture in particle physics?



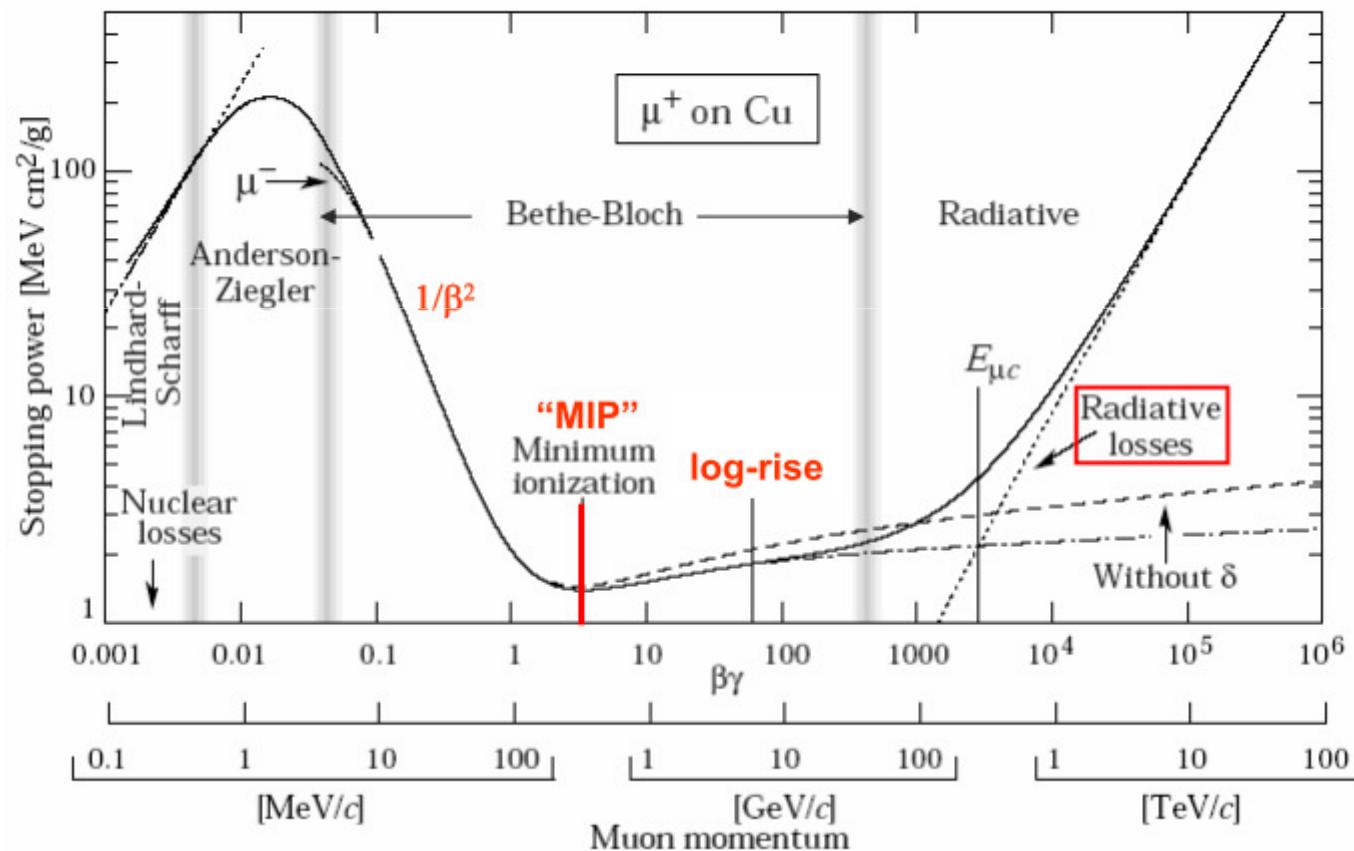
"**detector**" = (interaction) \otimes (sensor) \otimes (readout) \otimes (calibration) \otimes (analysis)
 \rightarrow complete chain has to be understood + controlled !

Interaction

50 MeV proton beam
on a
deuterium target



Interaction of Particles with Matter



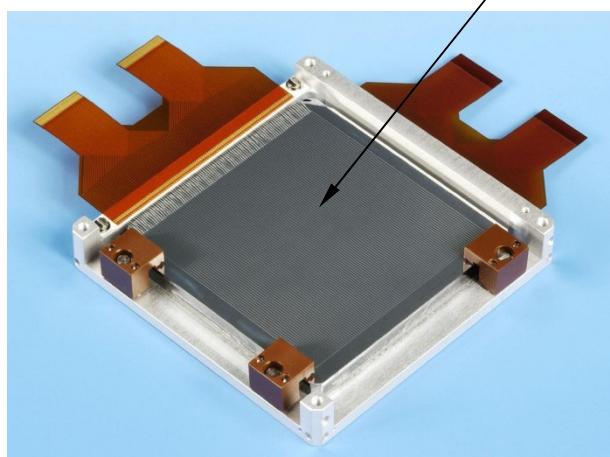
from dE/dx(MIP):
 Si: ~100 (e-h)/μm
 $(\epsilon = 3.6 \text{ eV}/(\text{e-h-pair}))$
 Ge: ~250 (e-h)/μm
 $(\epsilon = 2.9 \text{ eV}/(\text{e-h-pair}))$

for d > 10-100 μm
 $(10^3-10^4 \text{ e-h-pairs})$
 → "healthy signal"
 which can be well
 processed by low
 noise electronics

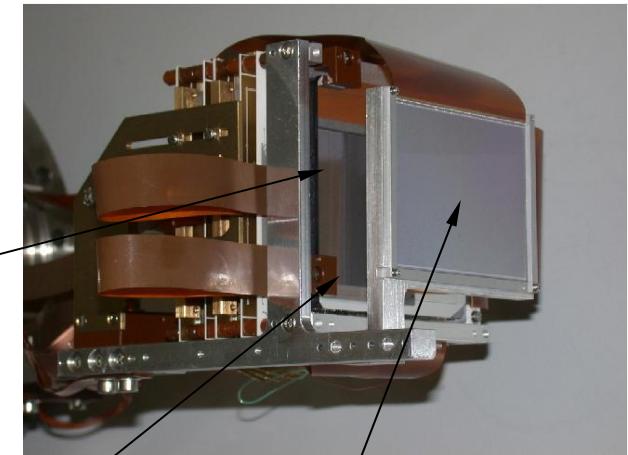
Silicon Tracking Telescopes

Range telescopes with 3 layers of x,y silicon detectors provide

1. $\Delta E/E$ particle identification and tracking
2. Energy determination of stopped particles
3. Self-triggering
4. < 1ns time-resolution



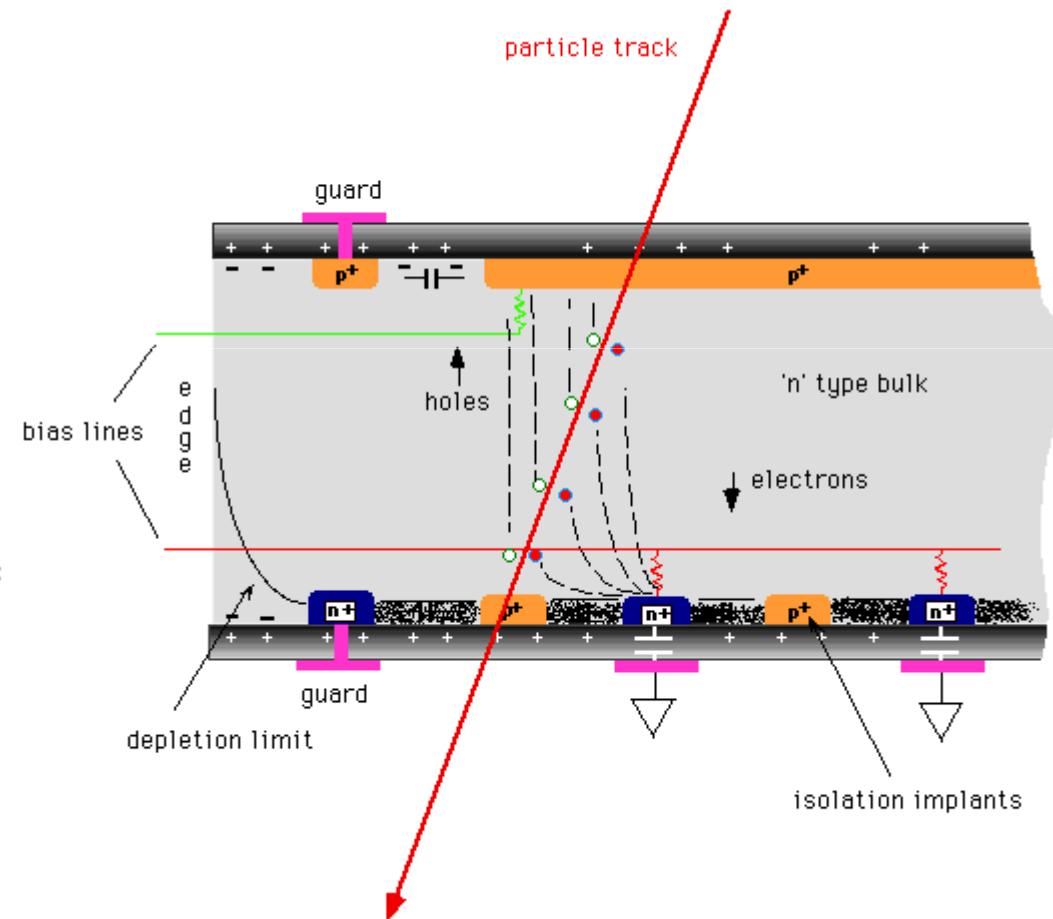
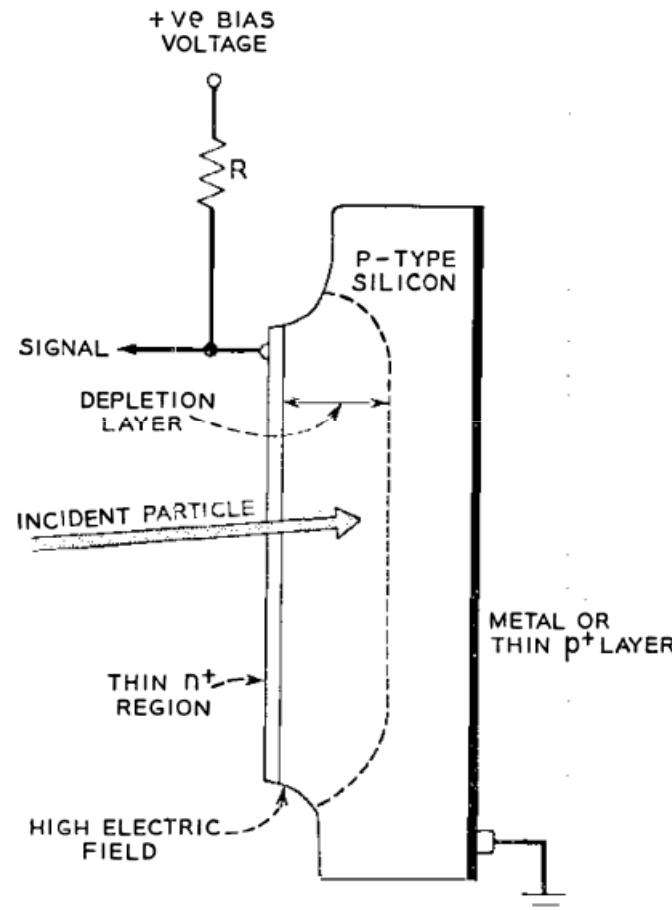
5100 μm thick Si(Li) detector



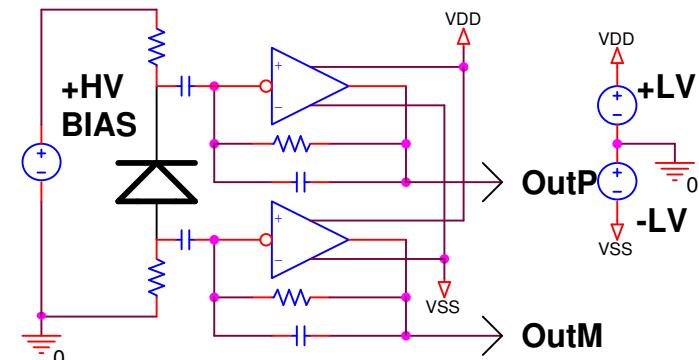
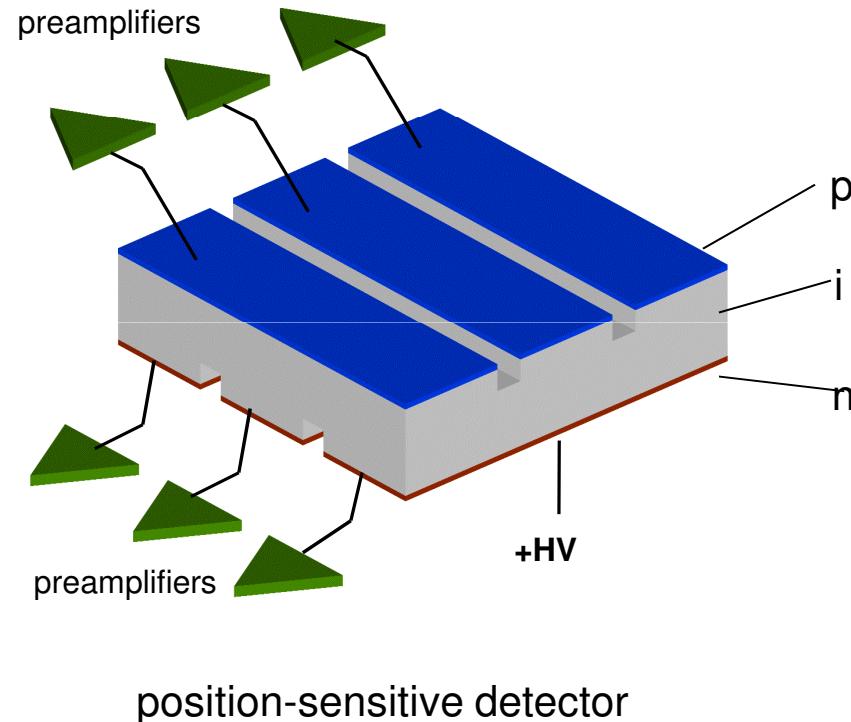
69 μm Si Detektor

300 μm Si detector (is missing in this picture)

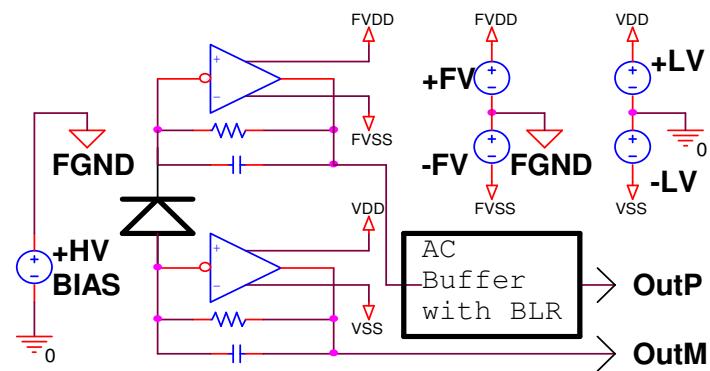
Charge Collection and Signal Formation



Processing of Electrical Signals

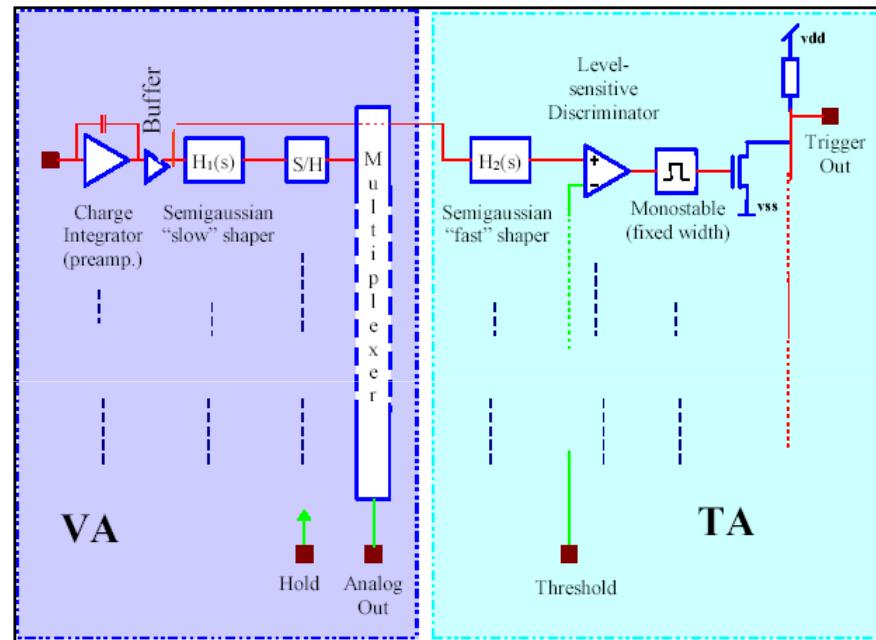


Capacitive connection of preamplifiers
(Bias 250 V - 2 kV)

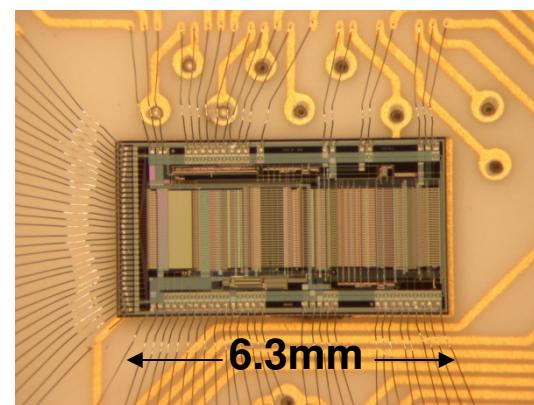


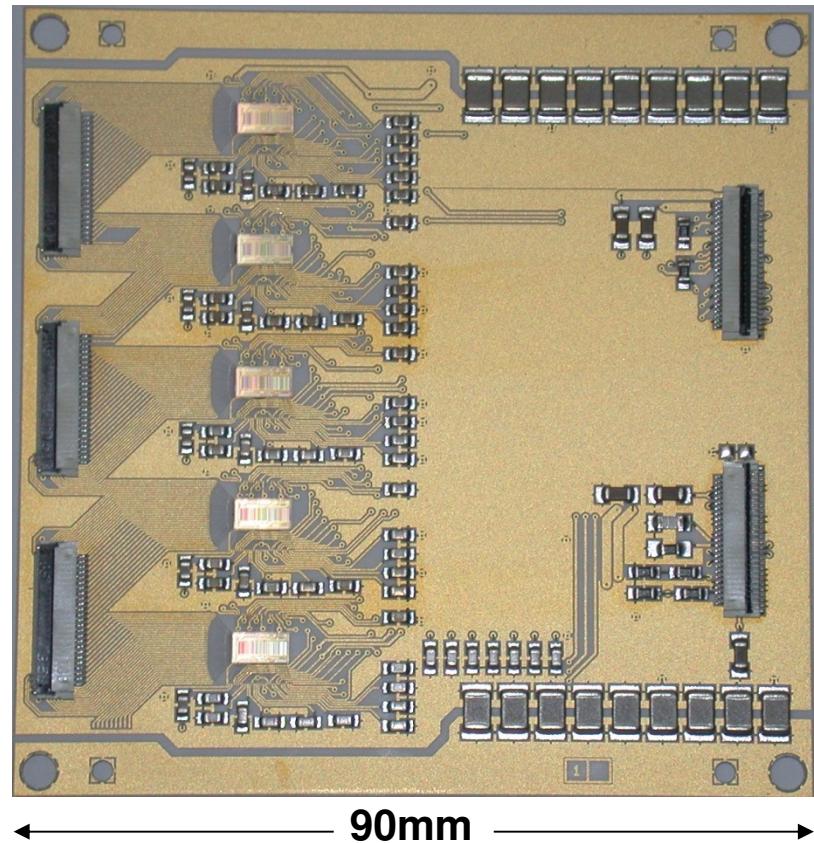
Floating power supply connection of
preamplifiers (Bias 0-100 V)

VA32TA2 self-triggering front-end electronics:

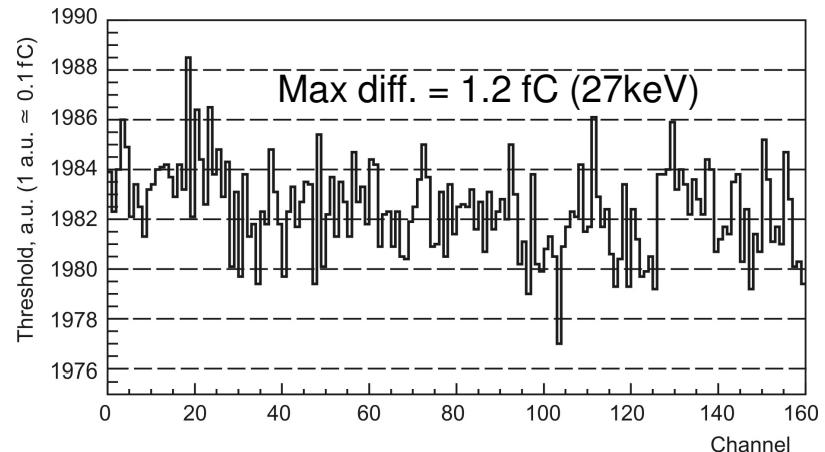


Number of channels	32
Technology	0.8 µm CMOS
Power supply	±2 V
Power dissipation	3 mW/channel
Linear range	11 MeV (±500fC)
Slow shaper (Peaking Time)	2 µs
Fast shaper (Peaking Time)	80 ns
Minimum Threshold	40 keV (1.8fC)
Threshold homogeneity	4 keV (0.2fC)
Time walk (0.05-11MeV)	~100 ns
Time resolution	$\sigma < 1$ ns
Energy resolution ($C_{det}=60\text{pF}$)	890 e ⁻ (sigma)
Readout frequency	10 Mhz

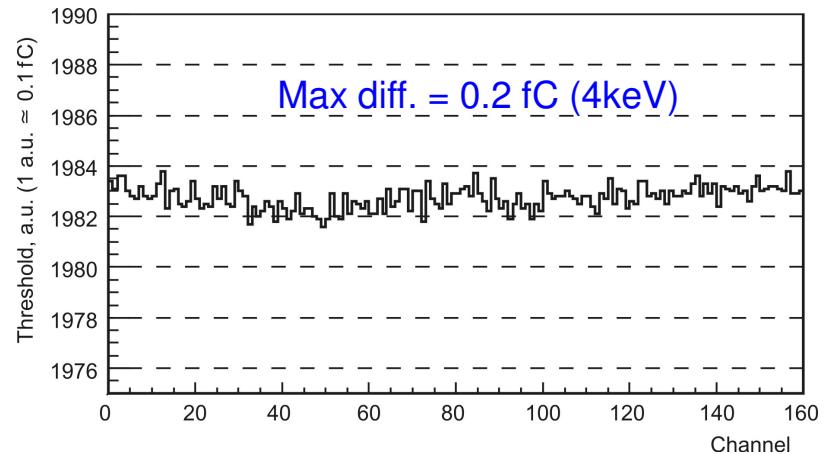




Before threshold DAC-tuning

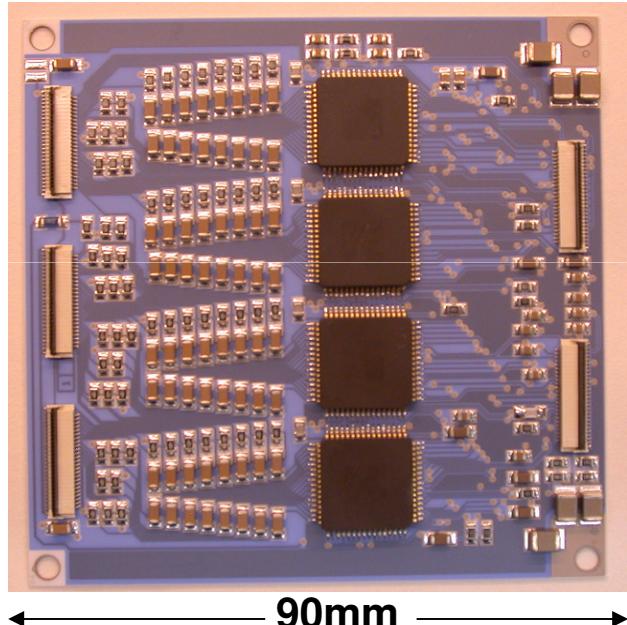


After threshold DAC-tuning



MATE3 self-triggering front-end electronics:

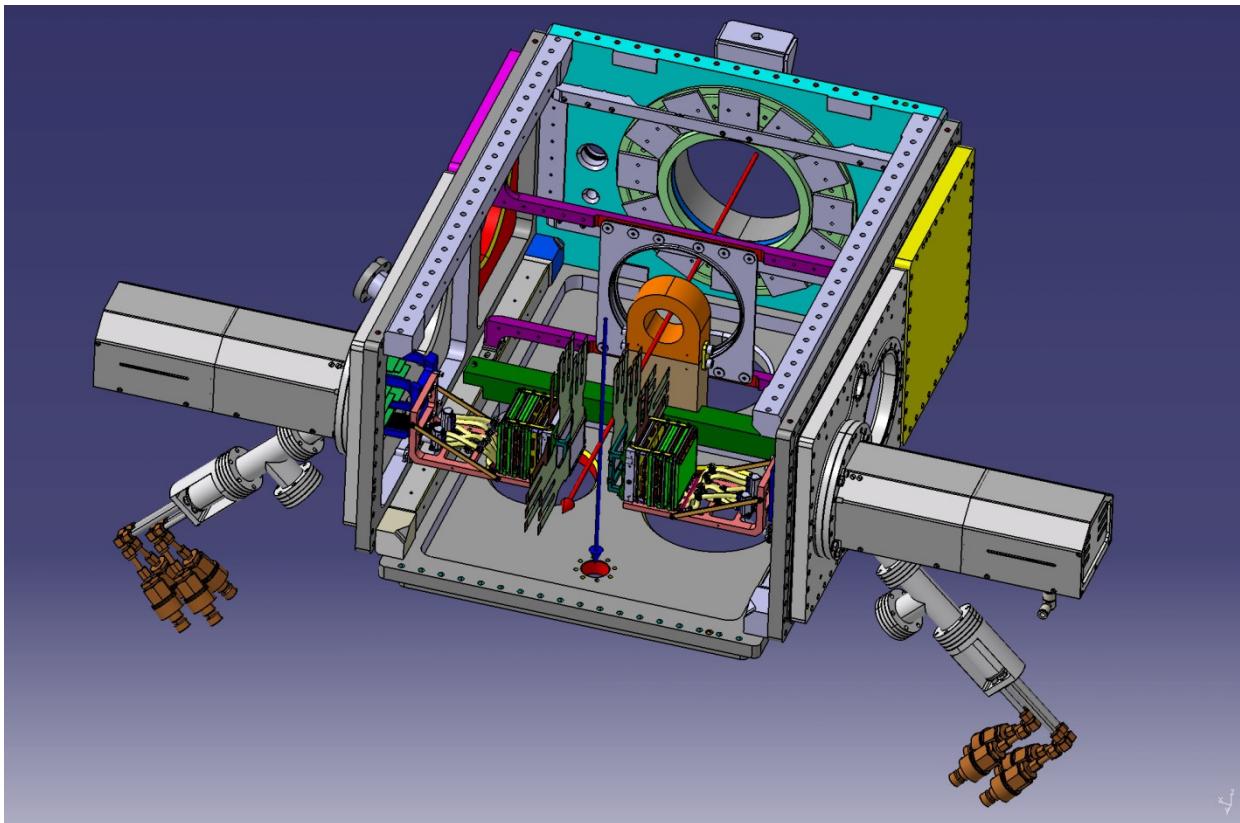
64 (128) channel MATE 3 board



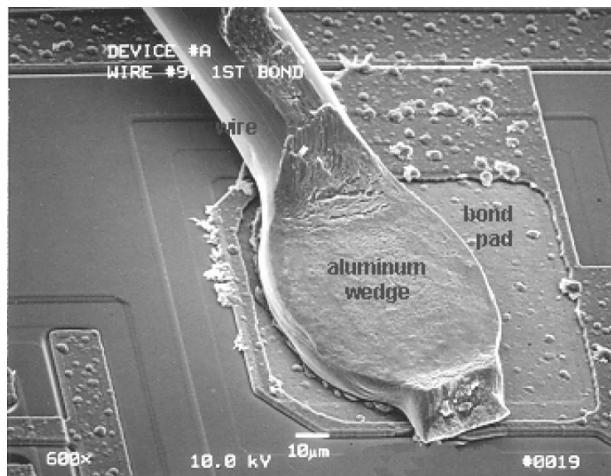
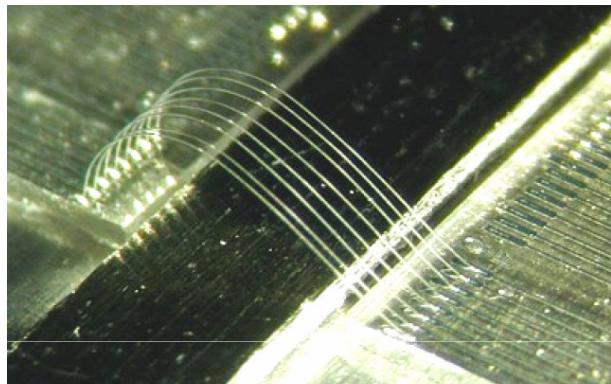
Parameters of the MATE 3 front-end chip

Number of channels	16
Technology	0.8 µm BICMOS
Power supply	±2.5 V
Power dissipation	30 mW/channel
Linear energy range	50 MeV (± 2220 fC)
Slow shaper (Peaking Time)	1 µs and 3 µs
Fast shaper (Peaking Time)	22 ns
Minimum trigger threshold	0.4 MeV (8fC)
Time resolution ($E > 1.5$ MeV)	$\sigma \leq 0.3$ ns
Energy resolution ($C_{det} = 60$ pF)	$\sigma = 1530$ e ⁻
Readout frequency	2 MHz (energy & time)
Common stop	reset needed

3D-Modeling for Design and Engineering



Bond Technology



Laboratory Infrastructure



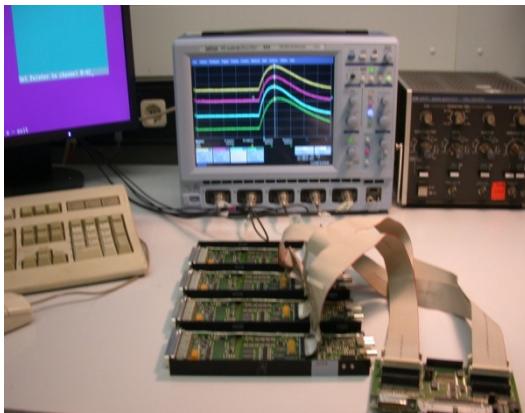
Nitrogen low humidity boxes



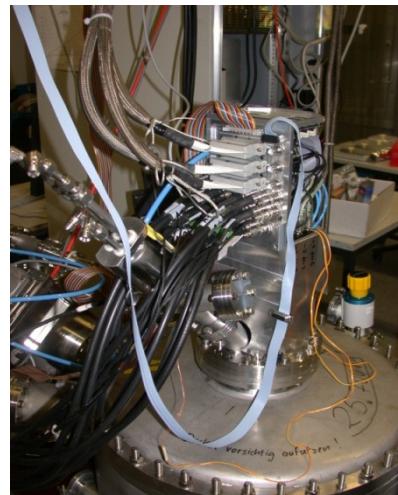
Mass spectrometer to check
vacuum compatibility



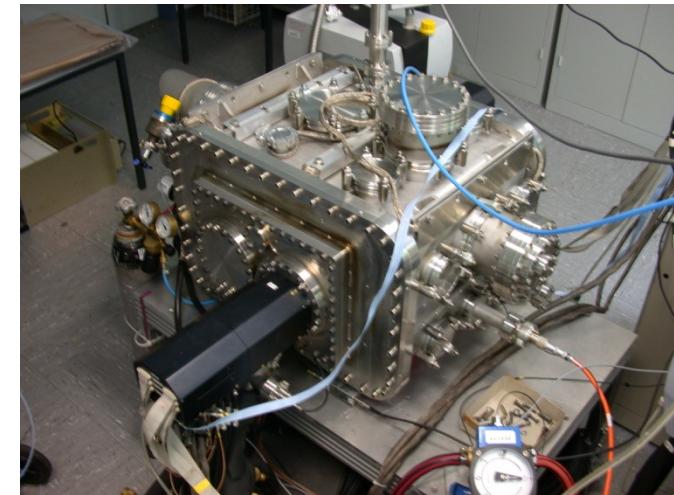
Clean room for assembly



Test stations for checking
electronics



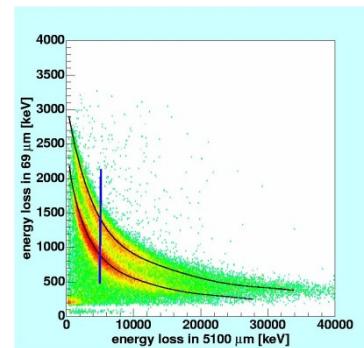
Test station for
temperature training



Vacuum chamber for test
and storage

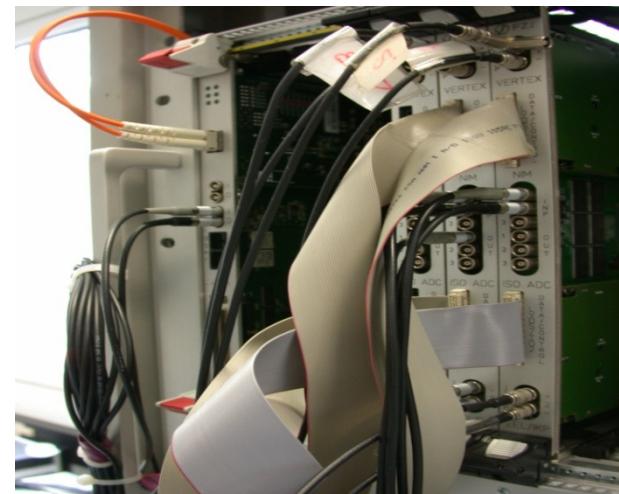
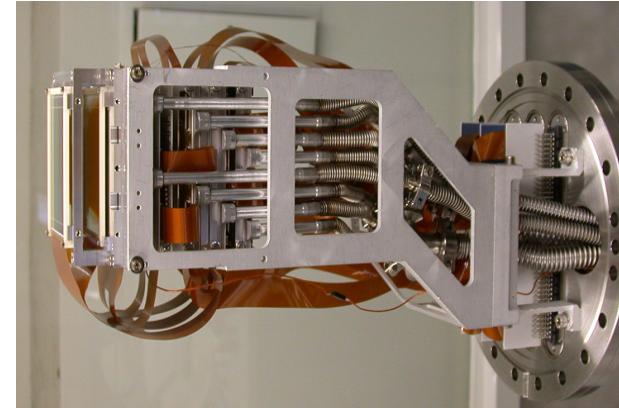
Key components to build the detection system:

- Detectors with front-end electronics.
- Cooling system for detectors, pre-amplifiers, and front-end electronics in vacuum.
- DAQ system to provide control and read-out of front-end electronics.
- Trigger system
- HV Bias and Low Voltage power supply system
- Independent monitoring systems
- Monitoring and control software
- Interlock protection systems
- Data analysis



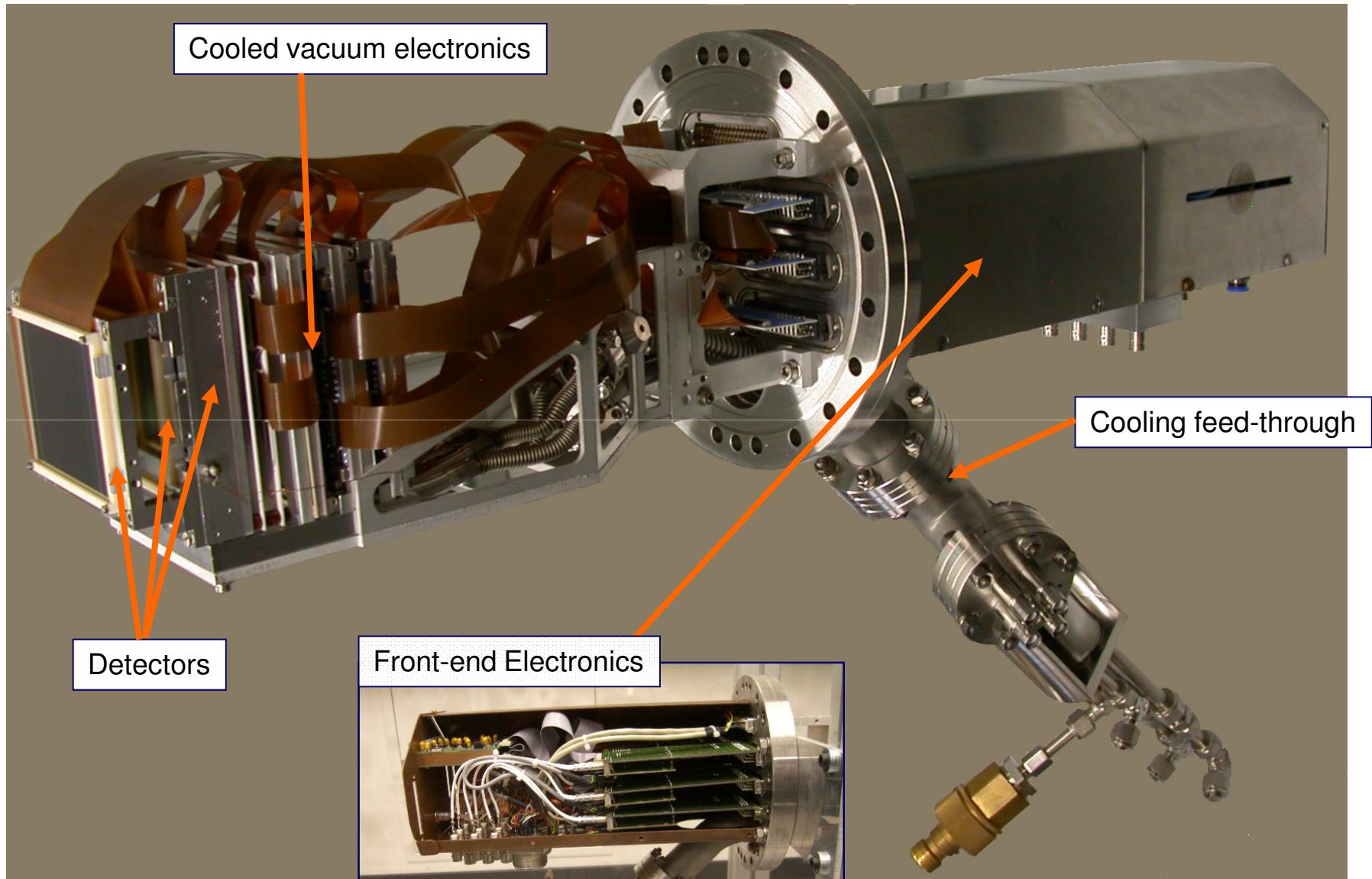
9. August 2012

GGSWBS'12 (August 6-10), Tbilisi, Georgia



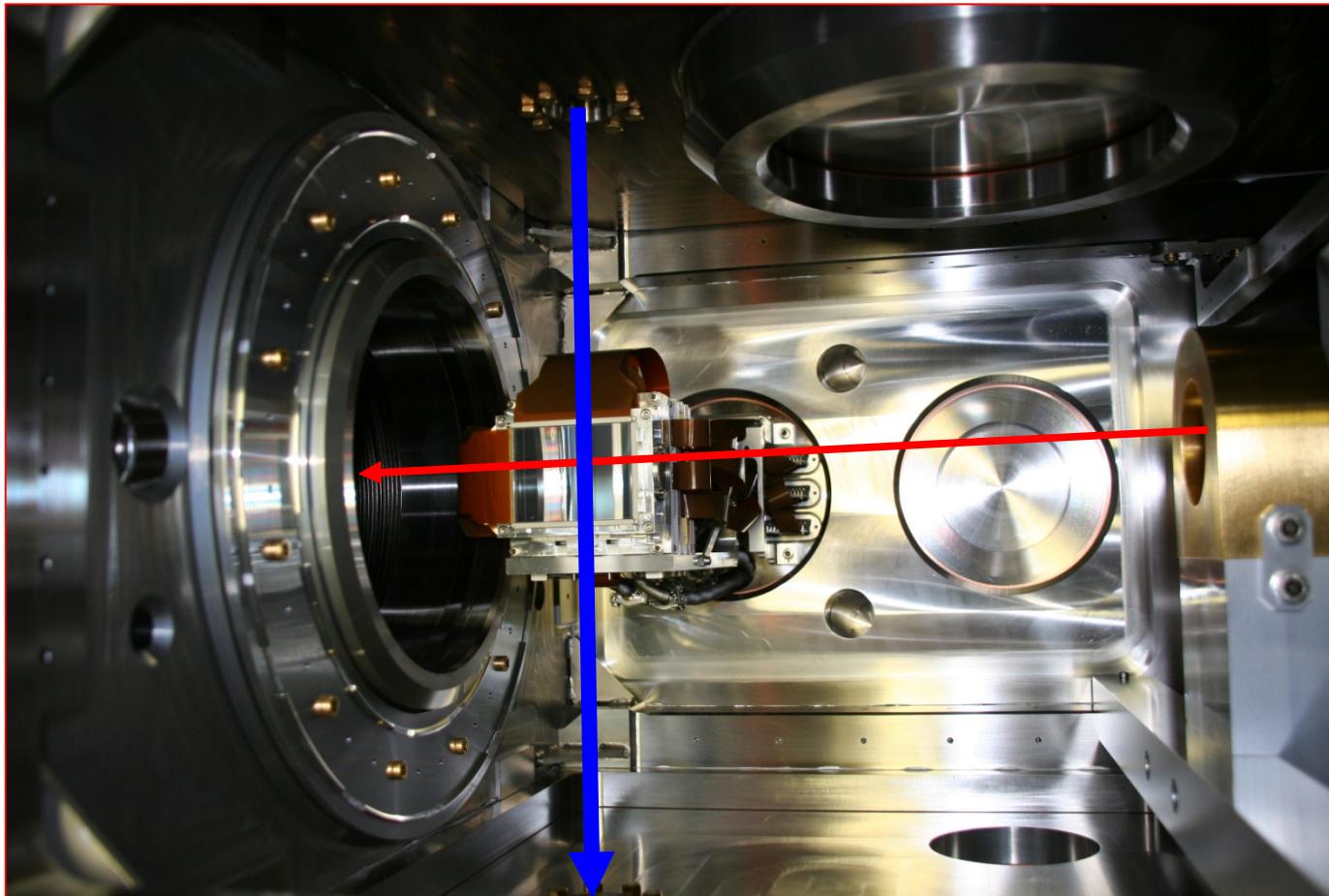
Ralf Schleichert

Silicon Tracking Telescope



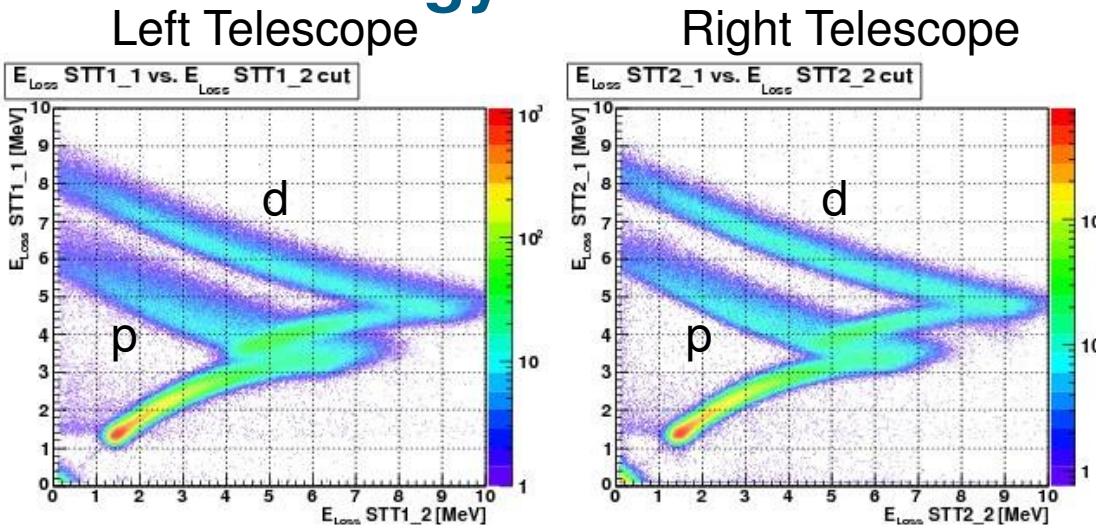
Silicon Tracking Telescope in the ANKE target chamber

Cluster Target Beam

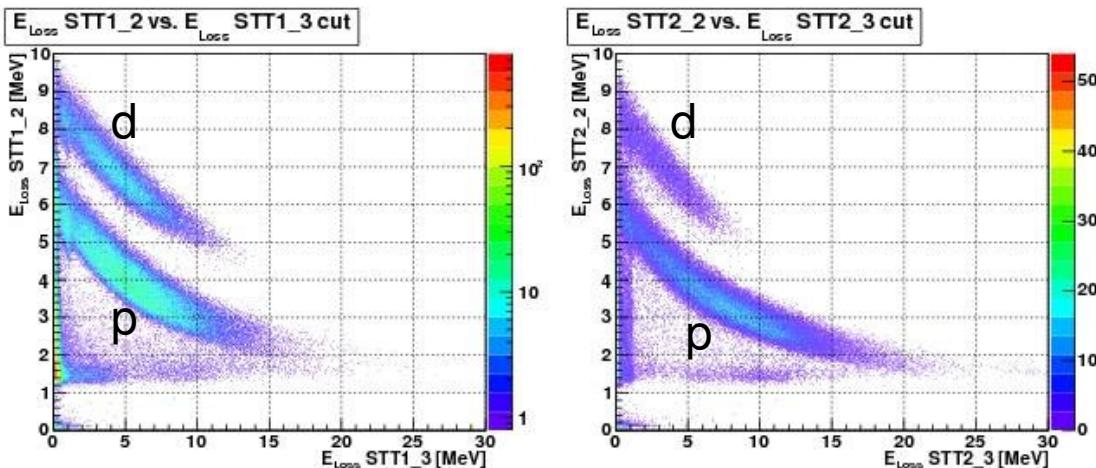


Detector Calibration: Energy

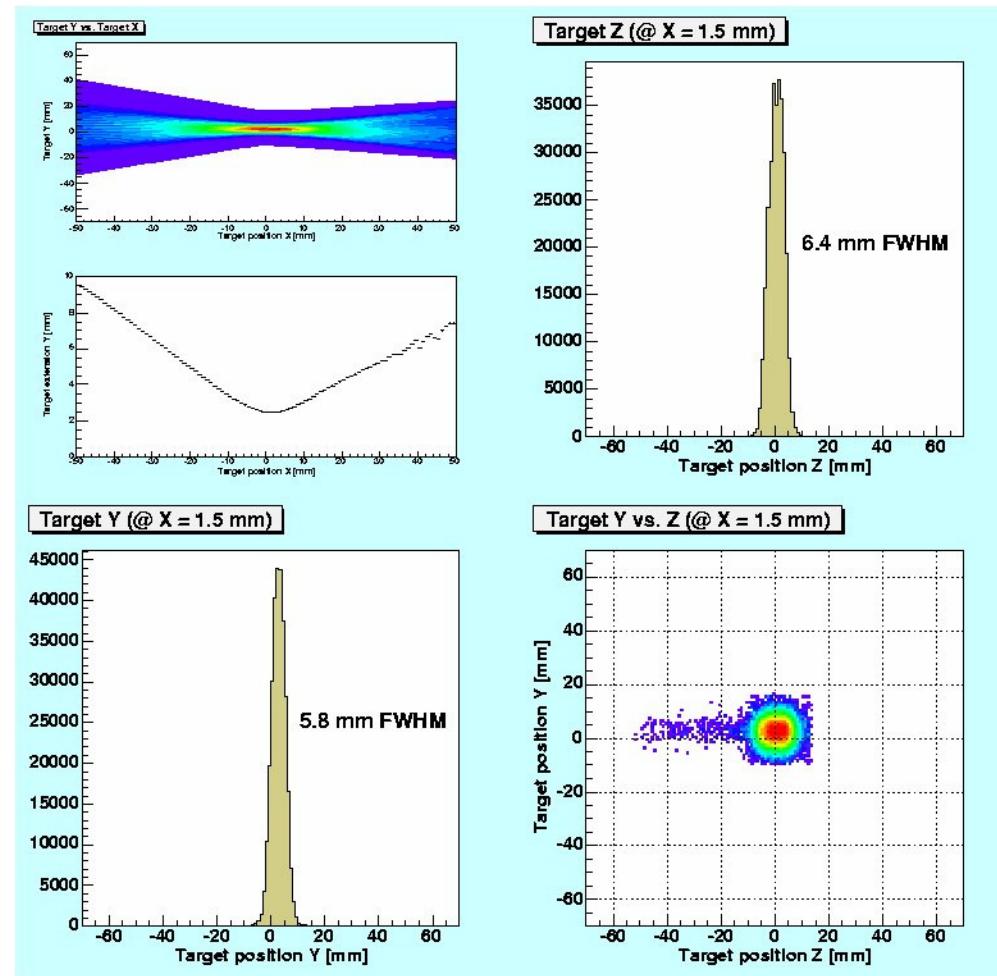
$\Delta E_1(300\mu\text{m})$ vs.
 $\Delta E_2(300\mu\text{m})$



$\Delta E_2(300\mu\text{m})$ vs.
 $\Delta E_3(5000\mu\text{m})$



Detector Calibration: Tracking



Science Result, a picture in particle physics

Physics case, experience, infrastructure, and the right team.

