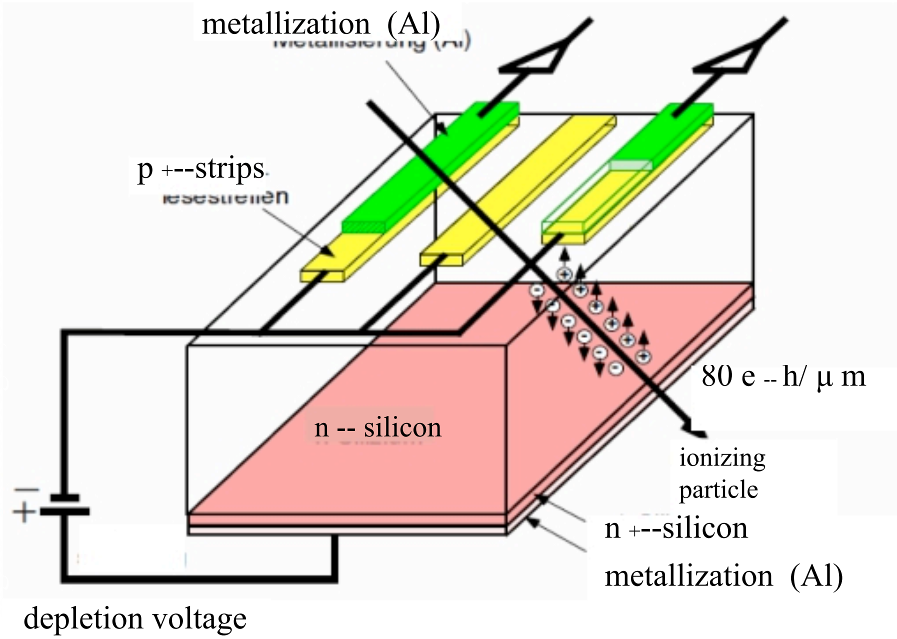
Strip Detectors

- First detector devices using the lithographic capabilities of microelectronics
- First Silicon detectors -- > strip detectors
- Can be found in all high energy physics experiments of the last 20 years



Principal: Silicon strip detector

- Arrangement of strip implants acting as charge collecting electrodes.
- Placed on a low doped fully depleted silicon wafer these implants form a one--dimensional array of diodes
- By connecting each of the metalized strips to a charge sensitive amplifier a position sensitive detector is built.
- Two dimensional position measurements can be achieved by applying an additional strip like doping on the wafer backside (double sided technology)

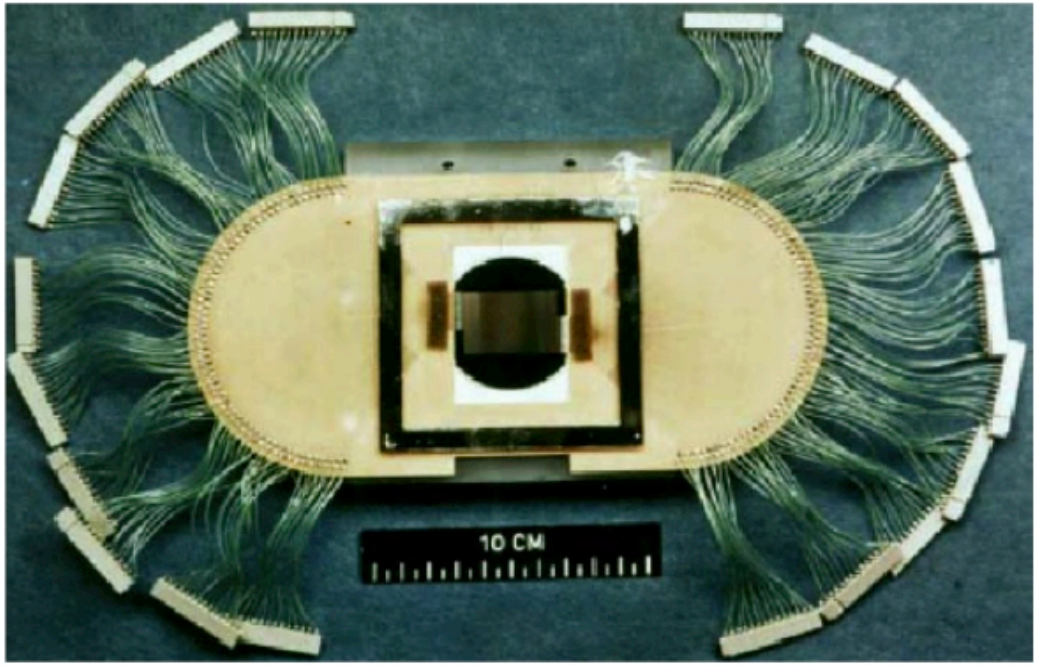
First HEP Application: NA11

- After discovery of charm (1974), τ -- lepton (1975) and beauty (1977) with lifetimes cτ ~100 μm : need fast (ns), and precise (μm) electronic tracking detectors

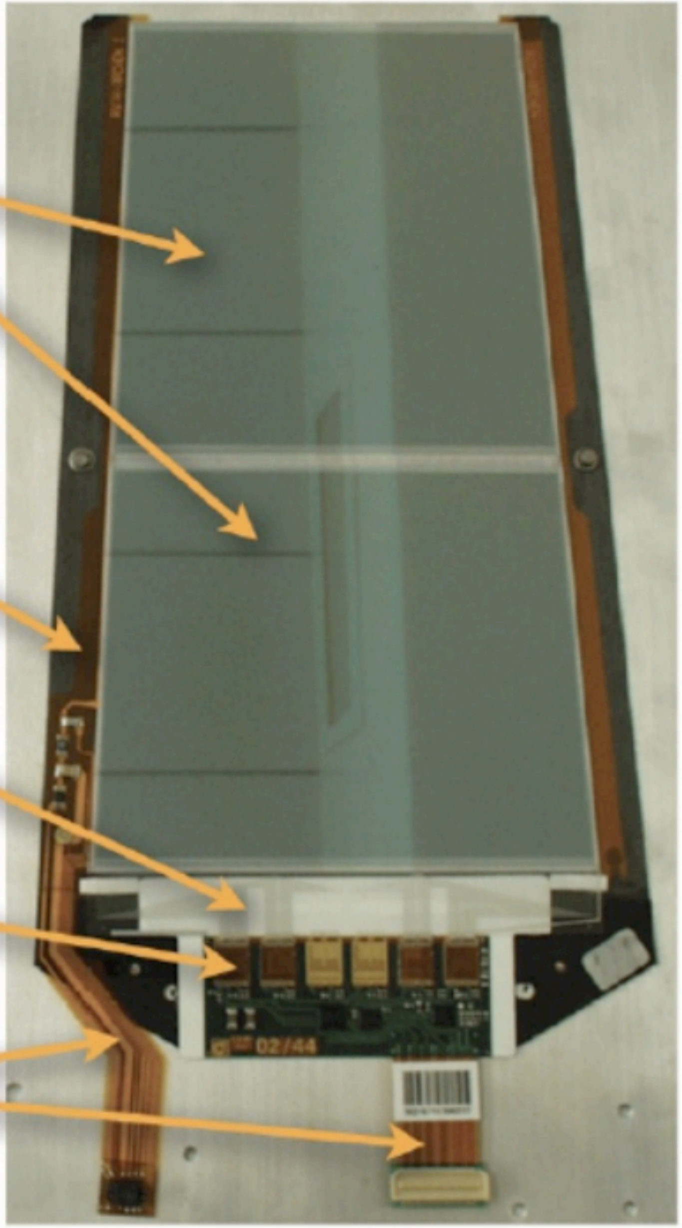
- strip detector for NA11 in 1981
  - 1200 strip-- diodes
  - 20 μm pitch
  - 60 μm readout pitch
  - 24 x 36 mm^2 active area ~0.01m^2
  - position resolution ~5.4 μm
  - 8 layer at the start

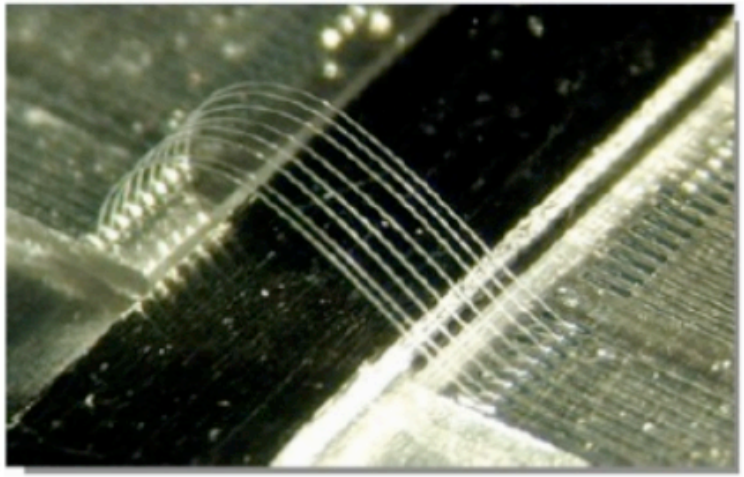
➔ precise track reconstruction

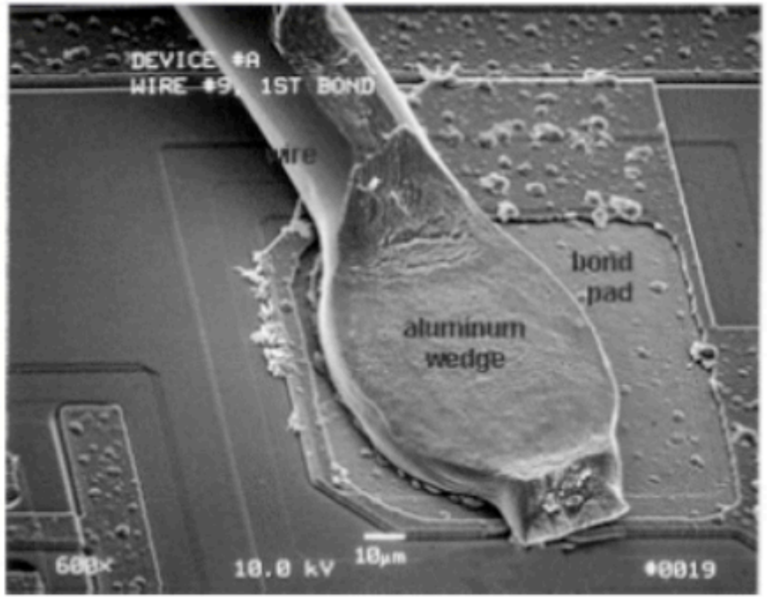
- readout electronic: ~1m^2!



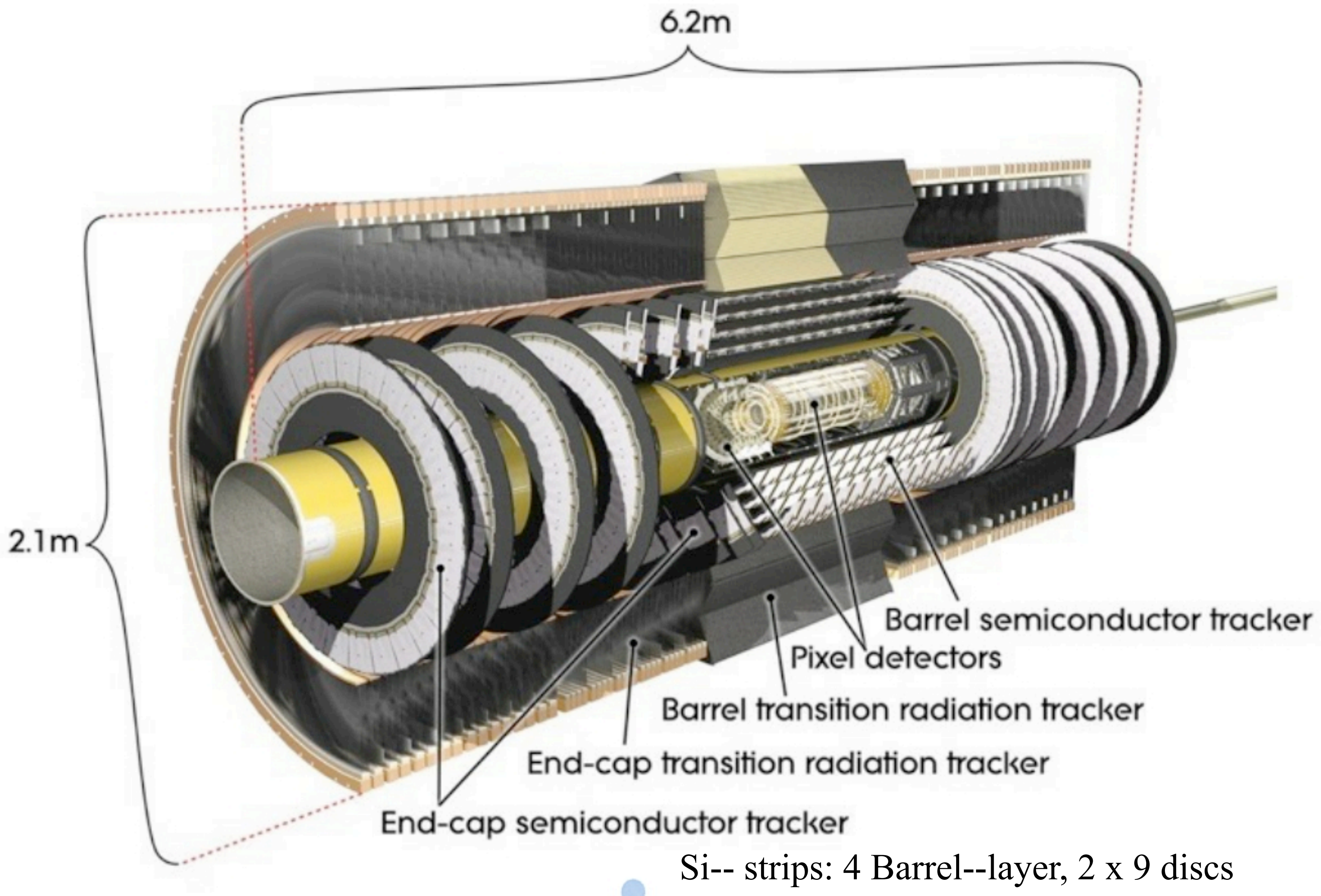
Strip Module CMS







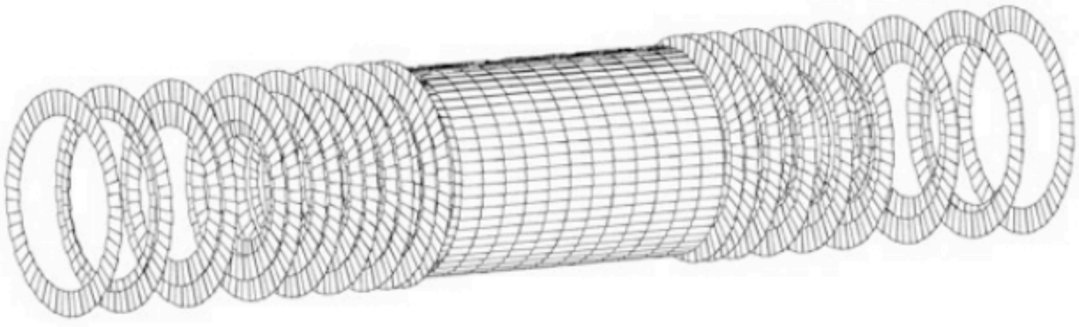
ATLAS SCT

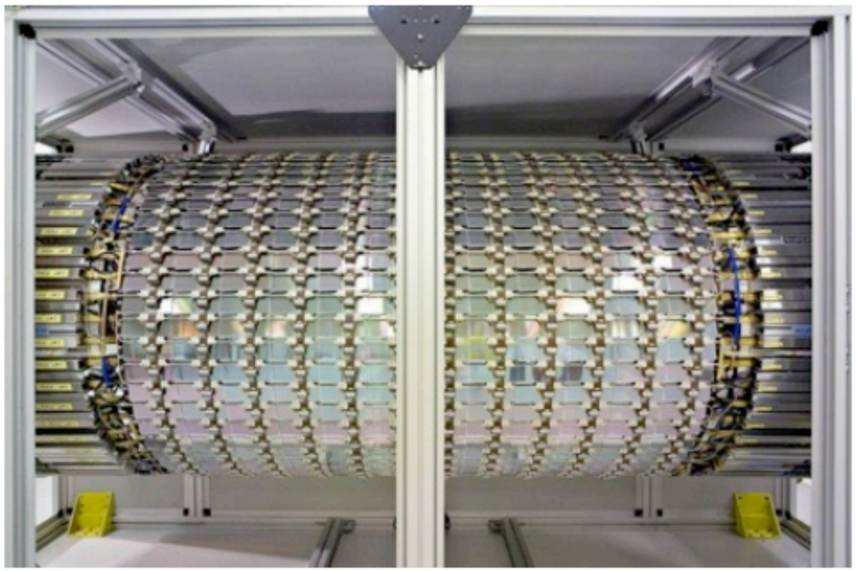


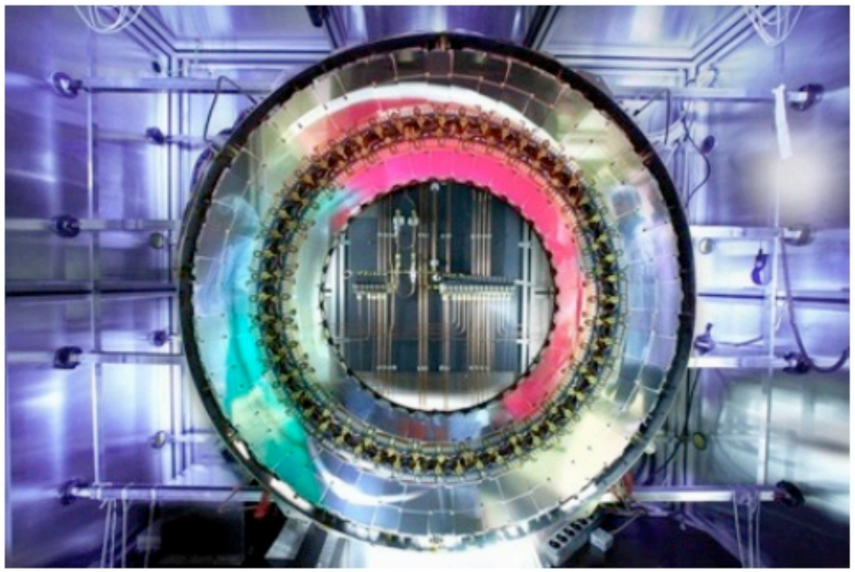
Si-- strips: 4 Barrel--layer, 2 x 9 discs

ATLAS SCT

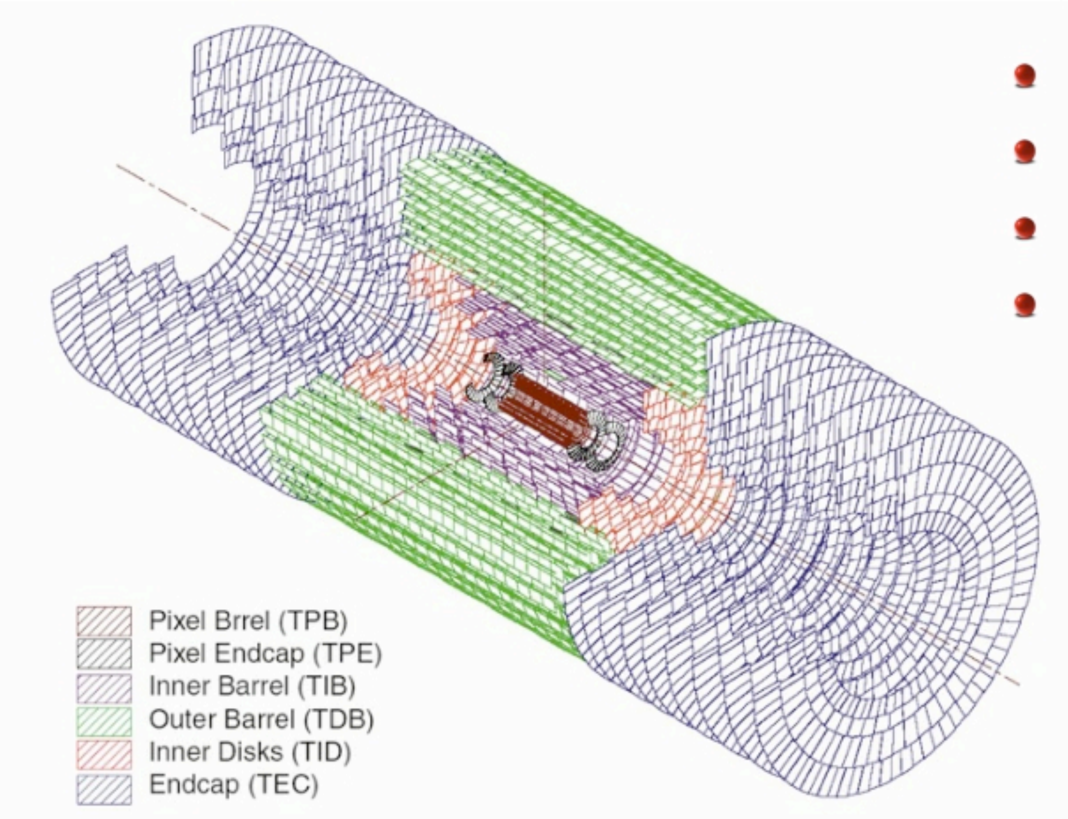
- 61 m^2 silicon, ~6.2 M channels
- 4088 modules, 2112 barrel (1 type), 1976 in the discs (4 different types)



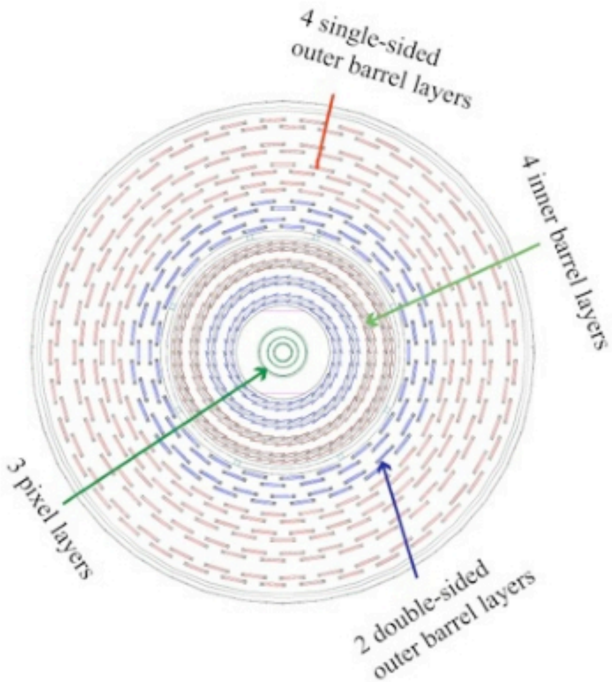




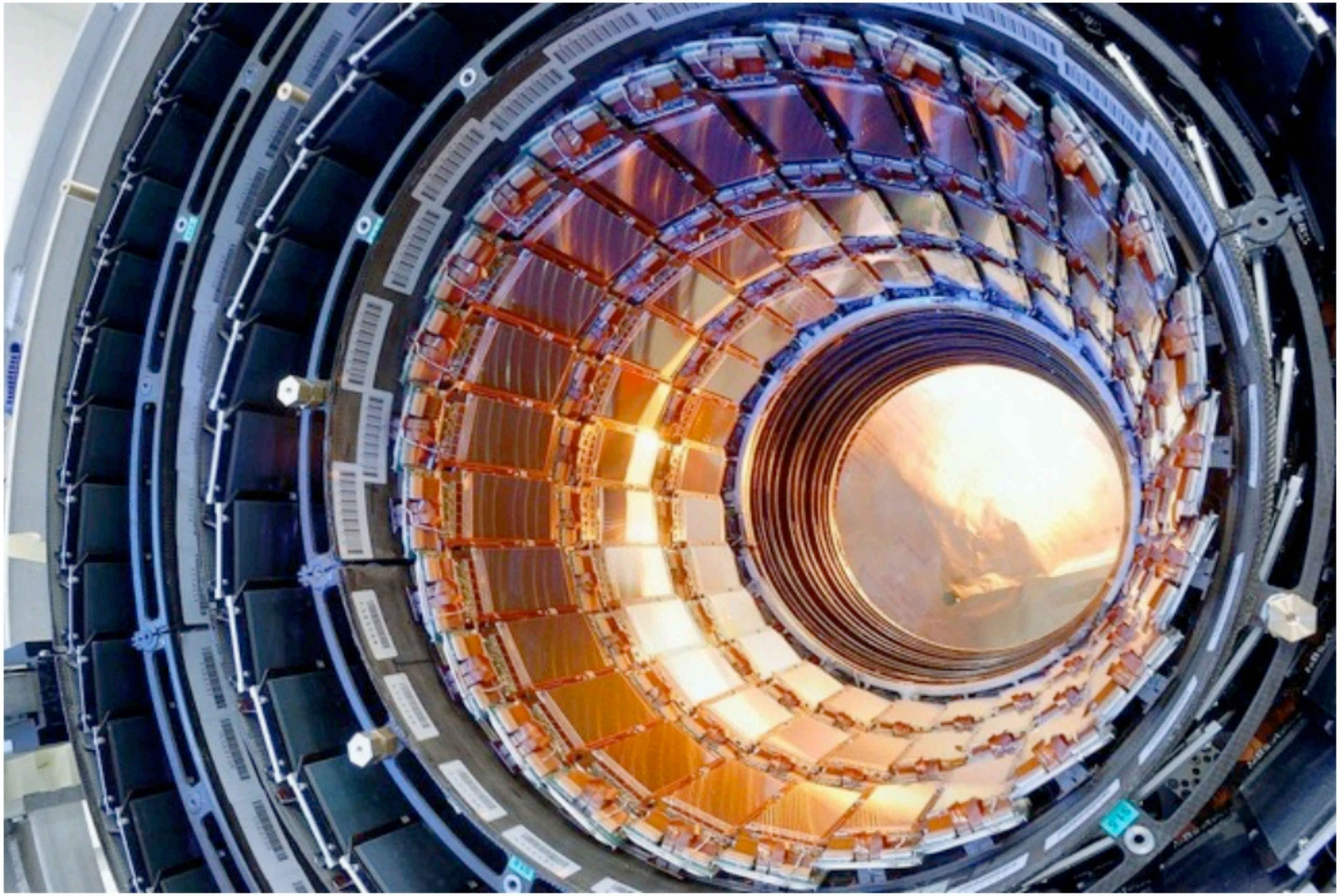
CMS Si --Tracker



- ~ 210 m^2 Silicon
- 25 000 Sensors, 9.6 M channels
- 10 barrel layers, 2x 9 discs
- The largest silicon tracker ever built

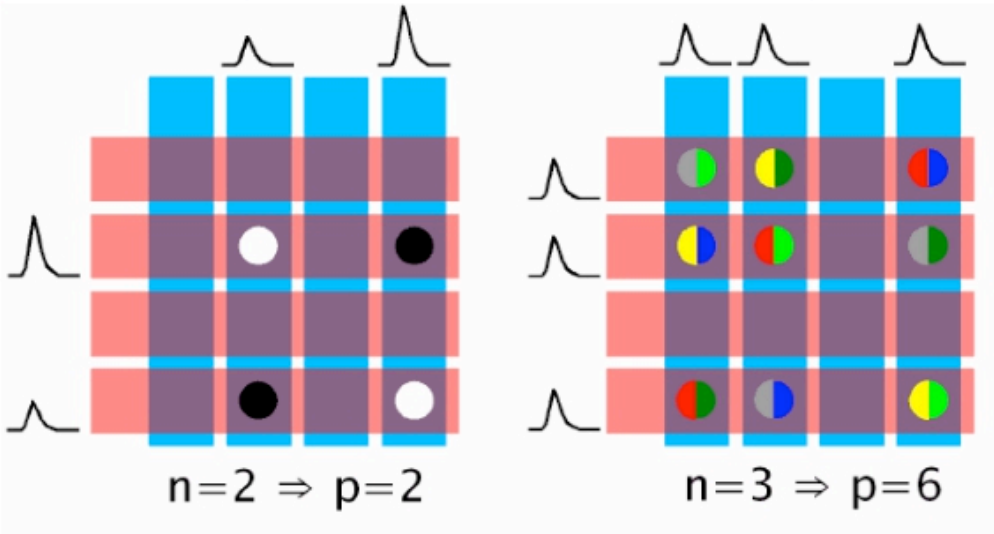


CMS Tracker -- Beauty Shot

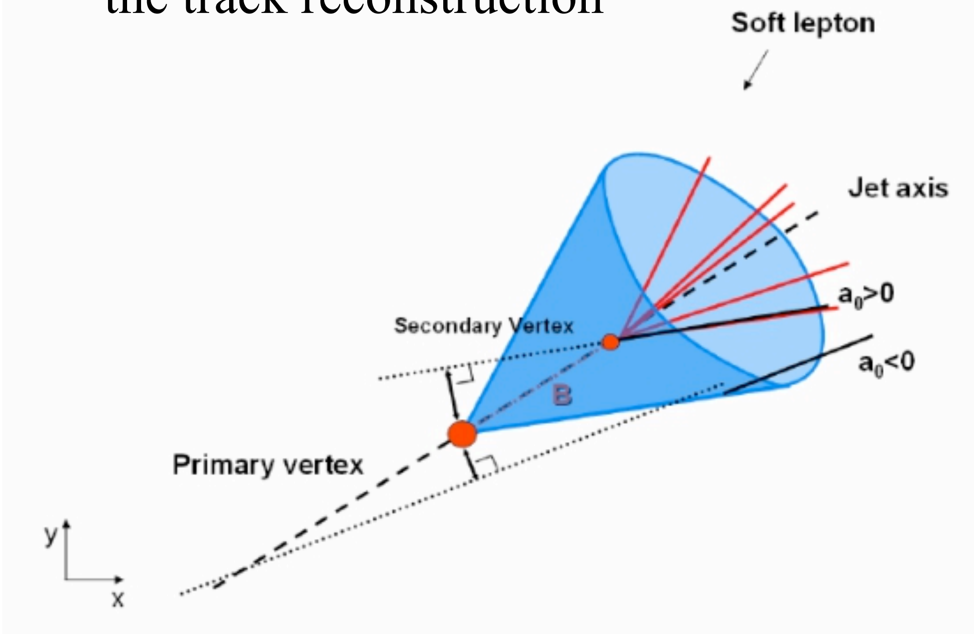


Pic:CERN

Limits of Strip Detectors



- In case of high particle fluences ambiguities give difficulties for the track reconstruction



- Deriving the point resolution from just one coordinate is not enough information to reconstruct a secondary vertex
- Pixel detectors allow track reconstruction at high particle rate without ambiguities
- Good resolution with two coordinates (depending on pixel size and charge sharing between pixels)
  - Very high channel number: complex read --out
  - Readout in active area a detector

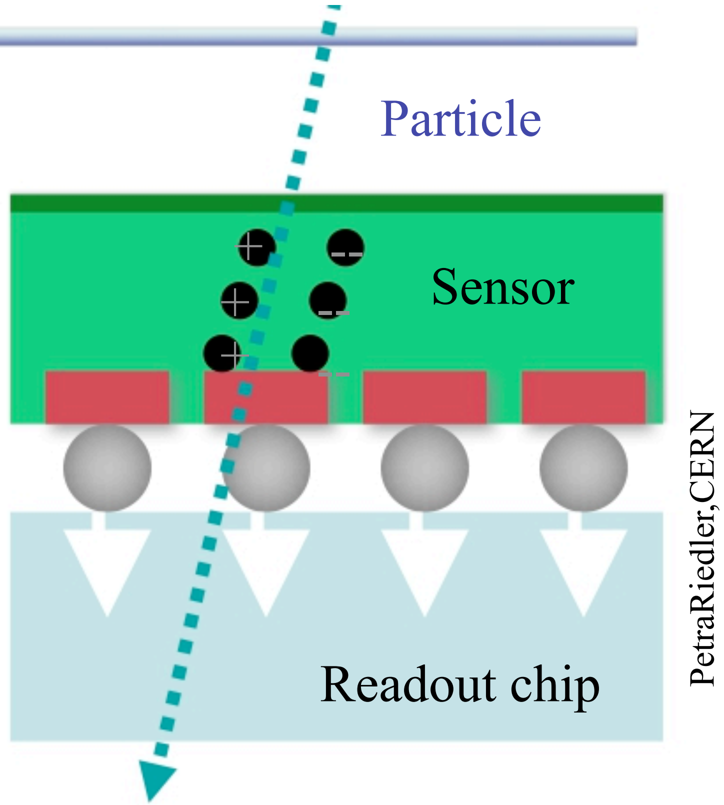
First pixels (CCDs) in NA11/NA32: ~1983

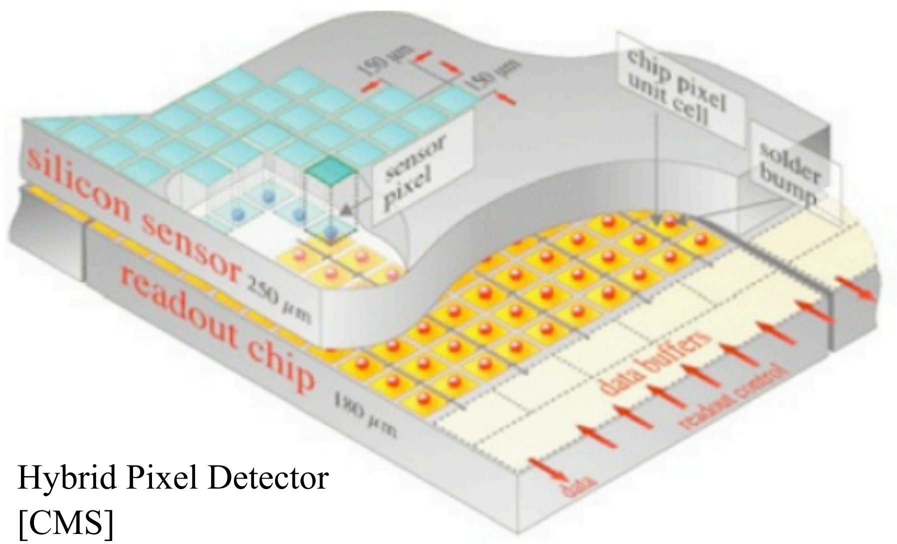
Hybrid Pixels – "classical " Choice HEP

- The read-- out chip is mounted directly on top of the pixels (bump-- bonding)
- Each pixel has its own read-- out amplifier
- Can choose proper process for sensor and read-- out separately
- Fast read-- out and radiation-- tolerant

… but:

- Pixel area defined by the size of the read-- out chip
- High material budget and high power dissipation

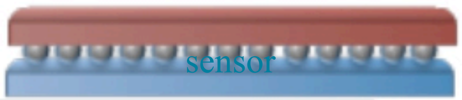


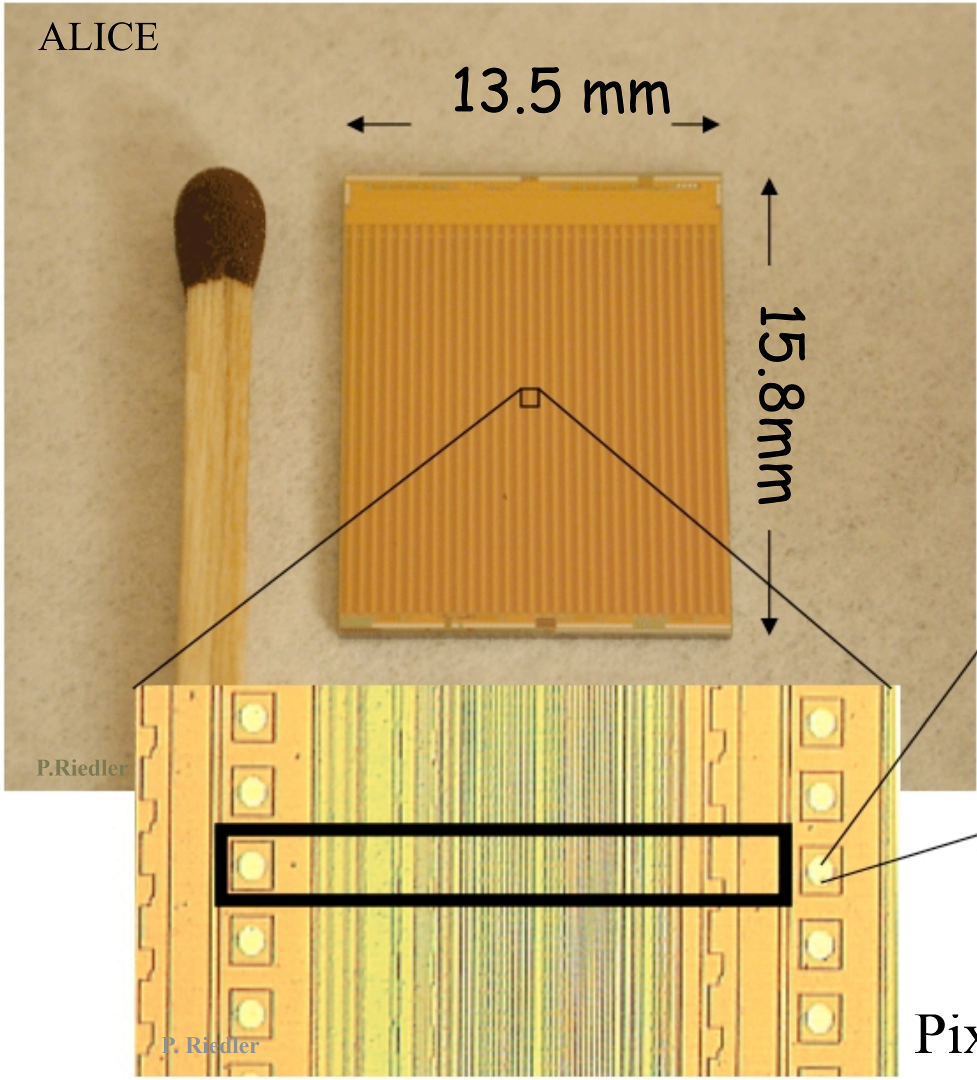


Hybrid Pixel Detector
[CMS]

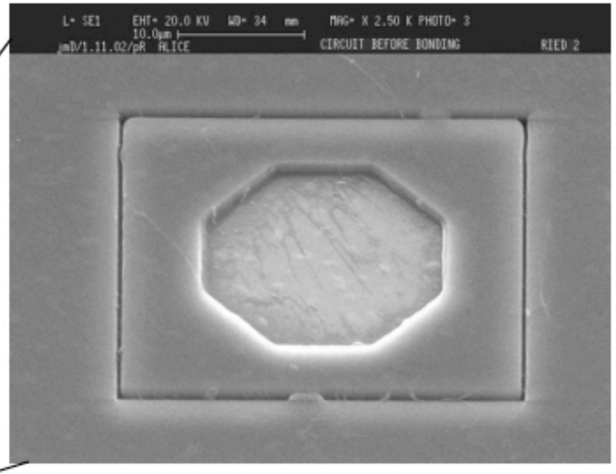
- CMS Pixels: ~65 M channels
  100 µm x 150 µm
- ATLAS Pixels: ~80 M channels
  50 µm x 400 µm (long in z or r)
- Alice: 50 µm x 425 µm
- LHCb
- Phenix
- ….

Hybrid Pixel Chip





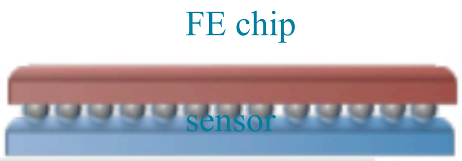
ASIC, custom design

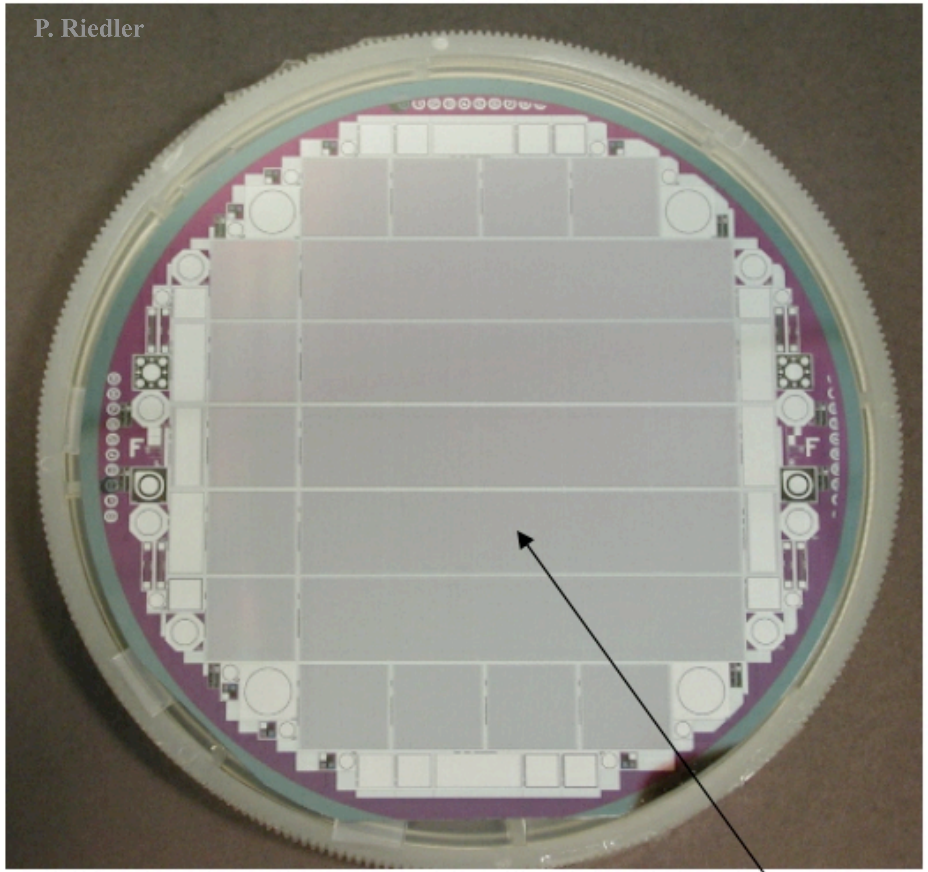


Bump bonding pad

Pixel cell (e.g. 50 µm x 425 µm)

Pixel Sensor





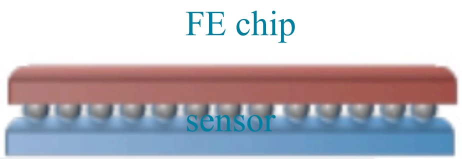
Different sensor materials can be used: Si, CdTe , GaAs, …

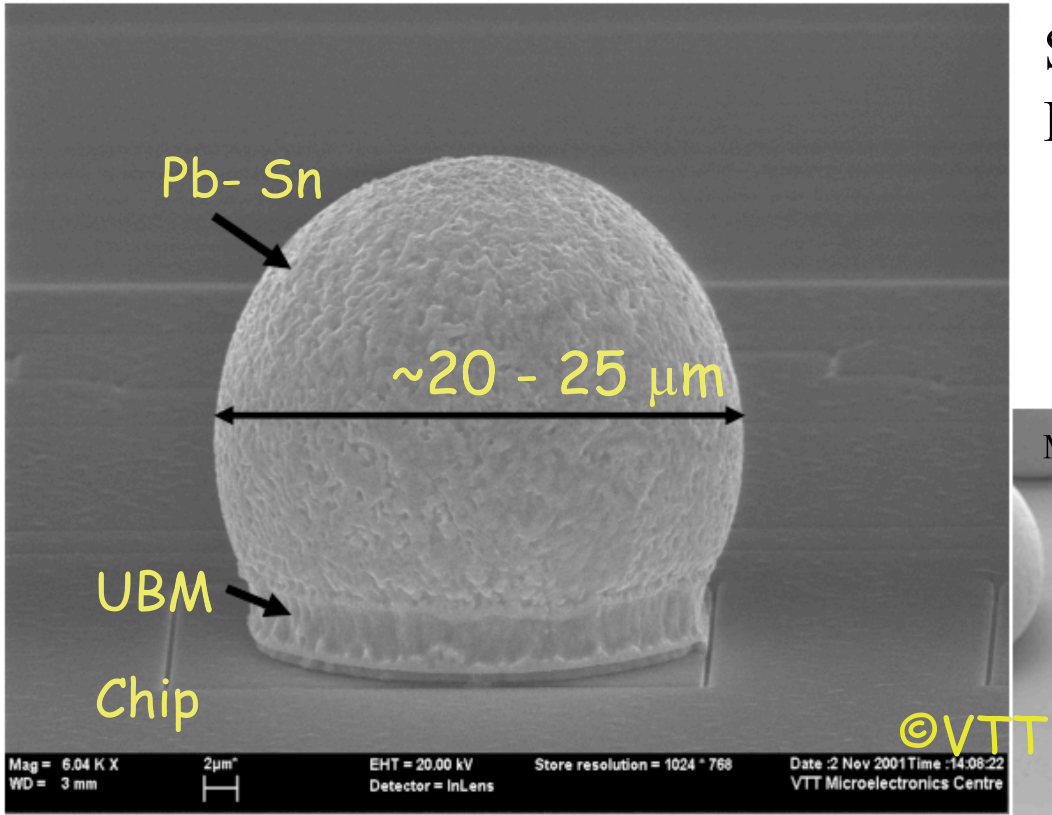
Depending on application (tracking, single photon counting, ..)

Usually several readout chips are connected to one sensor.

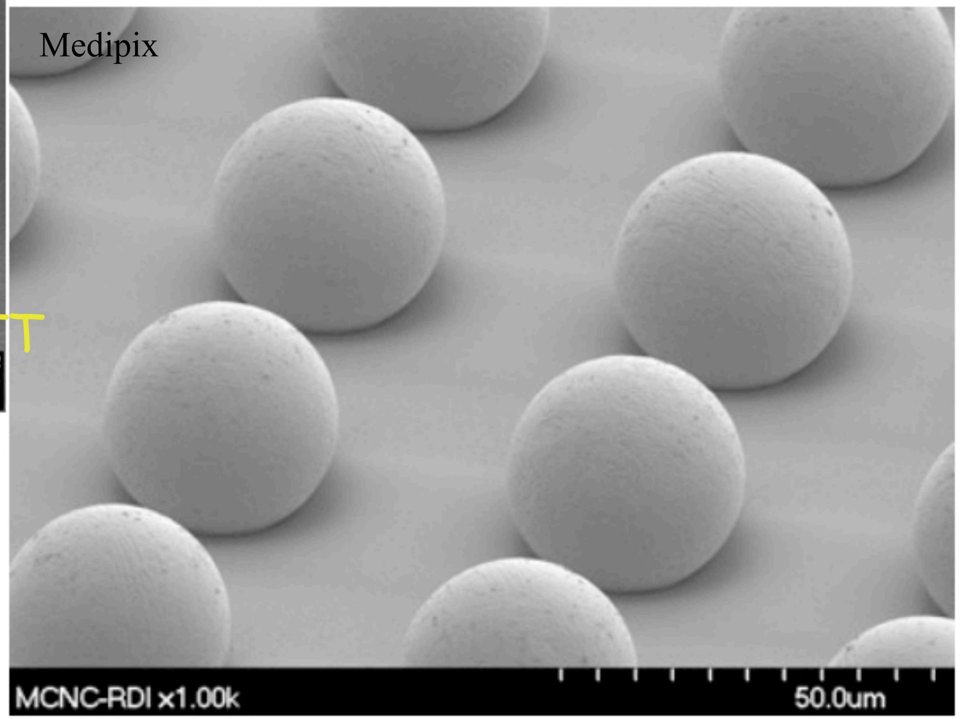
Pixel cell (50µm x 425µm)

Bump Bond





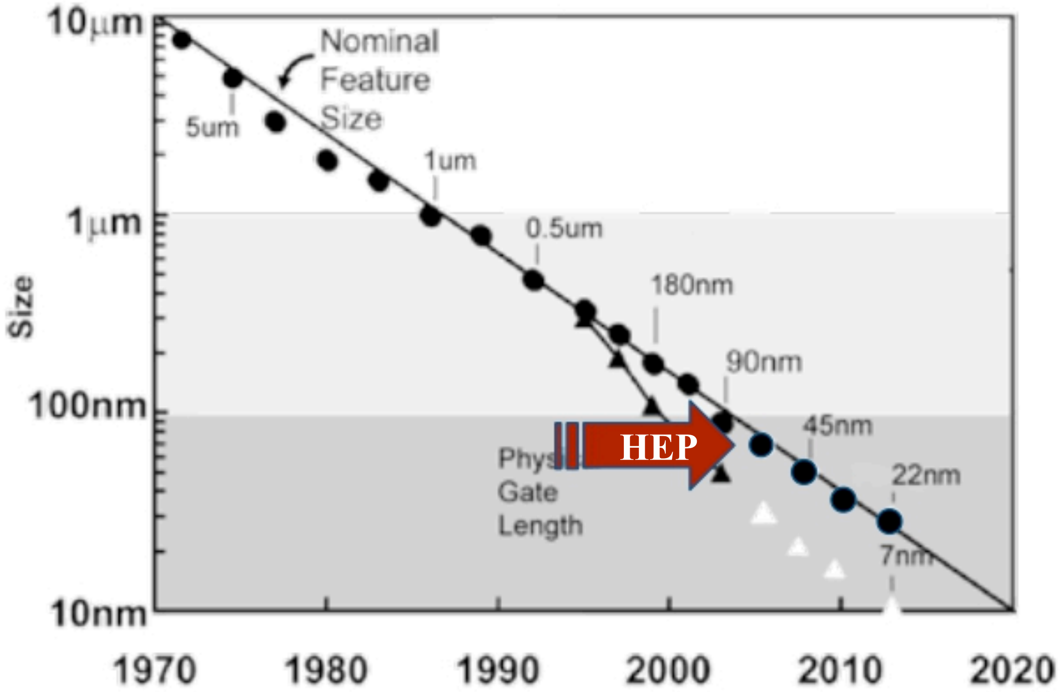
SEM picture of one Pb --Sn bump bond



Industry Scaling Roadmap

- New generation every ~2 years
- From 1970 (8 µm) to 2013 (22 nm) (industrial application)
- HEP nowadays at 130nm and 65nm

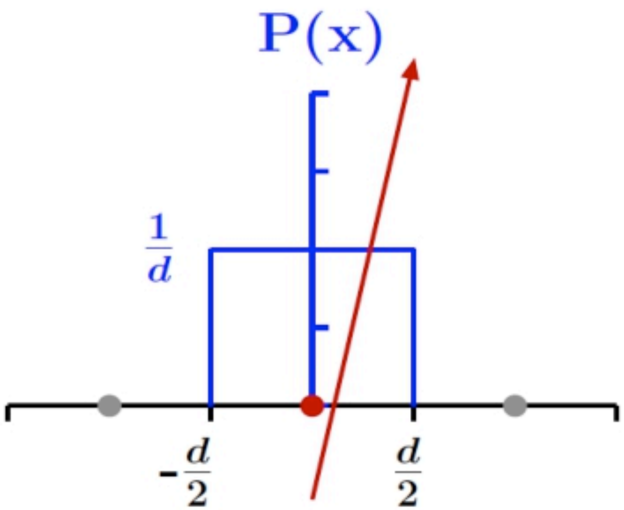
- Problem: by the time a technology is ready for HEP -- > "old" in industry standards.



Resolution of Tracking Detectors

- Depending on detector geometry and charge collection
- Strip pitch
- Charge sharing between strips

Simple case: all charge is collected in one strip



- Simple case: all charge is collected by one strip
- Traversing particle creates signal in hit strip
- Flat distribution along strip pitch; no area is pronounced

➔ Probability distribution for particle passage:

$$P(x) = \frac{1}{d} \qquad \Rightarrow \int_{-d/2}^{d/2} P(x)\,dx = 1$$

The reconstructed point is always the middle of the strip:

$$\langle x \rangle = \int_{-d/2}^{d/2} x\,P(x)\,dx = 0$$

Resolution of Tracking Detectors II

- Calculating the resolution orthogonal to the strip:

$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 \, P(x) \, dx = \frac{d^2}{12}$$

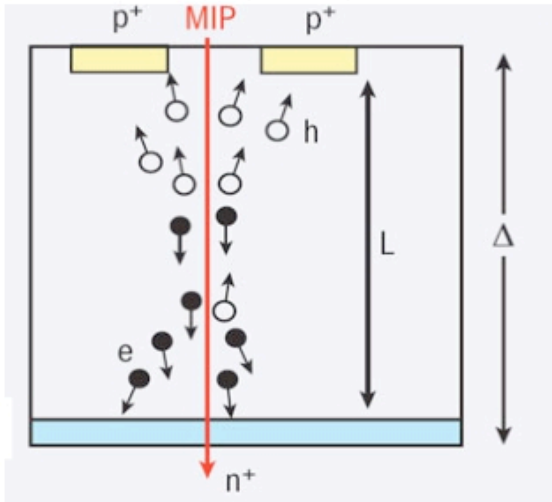
- Resulting in a general term (also valid for wire chambers):

$$\sigma = \frac{d}{\sqrt{12}}$$

- For a silicon strip detector with a strip pitch of 80 µm this results in a minimal resolution of ~23µm
- In case of charge sharing between the strip (signal size decreasing with distance to hit position)
- Resolution improved by center of gravity calculation

Charge Collection

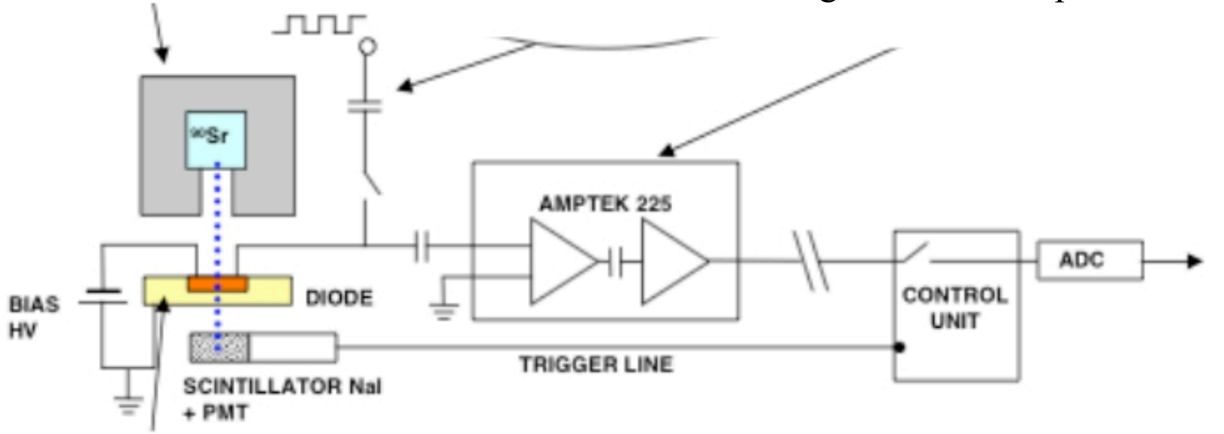
- Collected charge in a detector volume
  - important parameter which shows effects with radiation damage or other effects
  - charge induced by particles from a radioactive source, by a laser or test beam particles
  - measurement of CC in comparison to optimal value versus different parameters (**CC efficiency**)
    - bias voltage
    - radiation level
    - ….



Picture:U.C.DaVia

Example: with 90Sr source

particle source
calibration circuit
charge sensitive amplifier



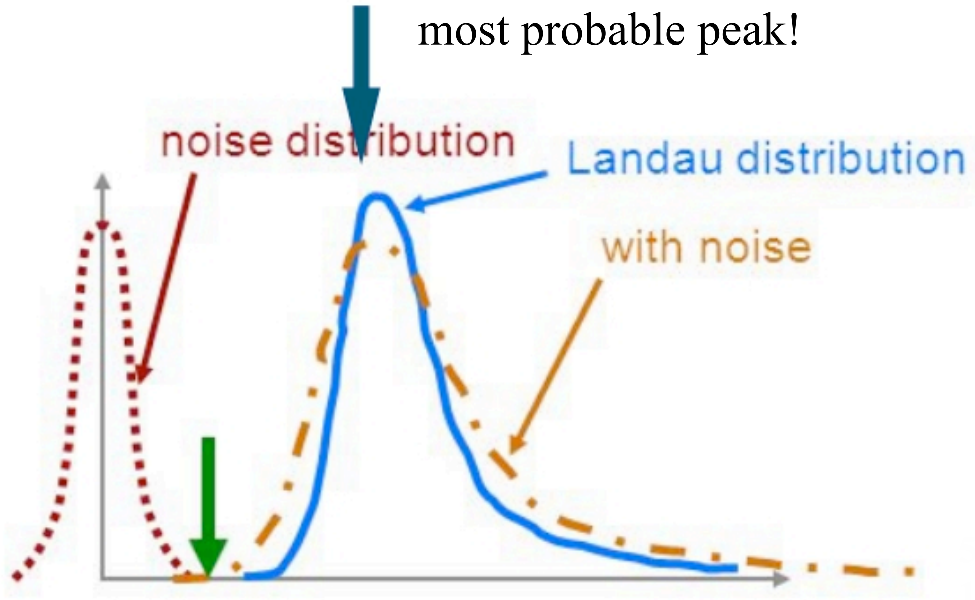
Silicon sensor

Picture:M.Bruzzi

Can be measured with bench top setup in a laboratory

Signal/Noise Ratio

- Signal size for a certain input signal over the intrinsic noise of the detector
  - parameter for analog signals
  - good understanding of electrical noise needed
    - noise measurements
    - noise simulations
  - signal induced by source or laser (or test beam particles)
  - optimal S/N is larger than 20



Detection Efficiency

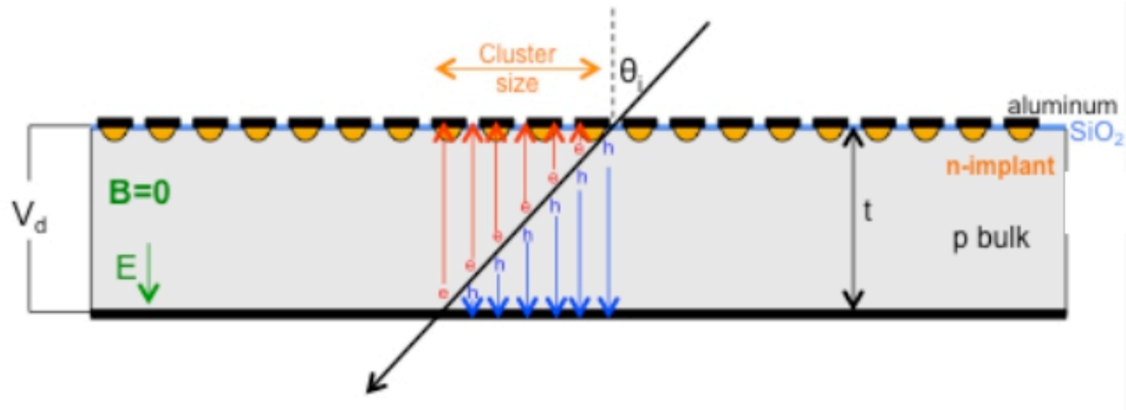
- **Detector efficiency** : ϵ probability to detect a transversing particle
  - should be as close to 100% as possible
  - i.e. 6 layer silicon detector with 98% efficiency per layer -- > overall tracking efficiency is below 90%
  - needs to be measured in test beam

$$\epsilon_{\mathrm{track}} = (\epsilon_{\mathrm{layer}})^n$$

n = number of layer is tracking system

- **Cluster size** : number of hit pixels/strips belonging to one track
  - usually given in unit of strips or pixels
  - depending on angle of incidence

Needs to be measured in test beam ….

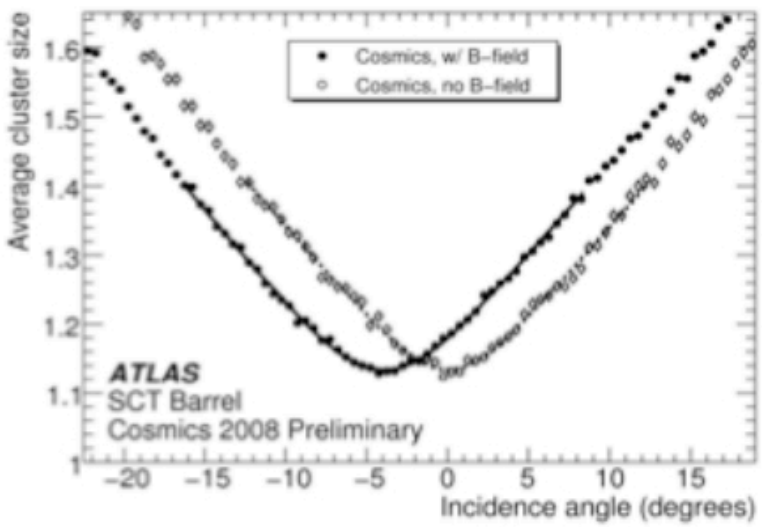


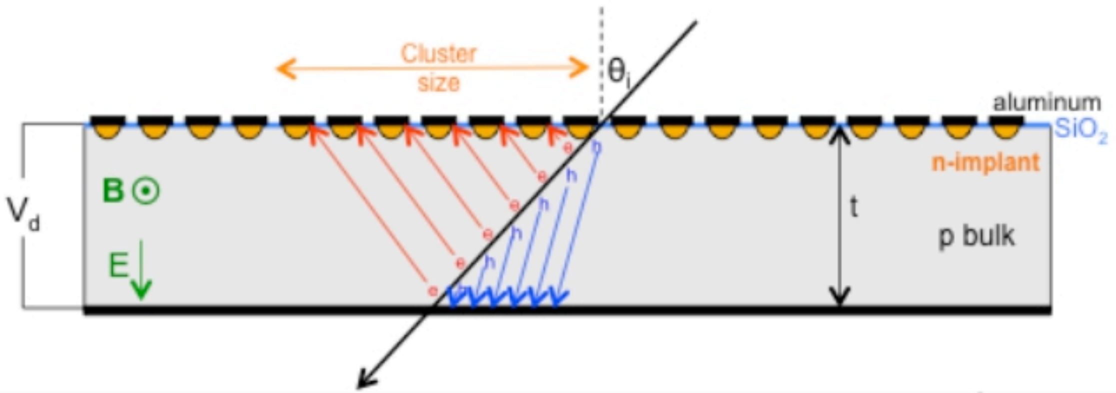
Lorentz Angle

- increase of cluster size due to Lorentz drift in a magnetic field
- Important parameter in particle physics as most tracking detectors operate in a magnetic field

$$\tan\theta_L = \mu_H B = r_H \mu_d B$$

Hall mobility — Hall factor — Drift mobility



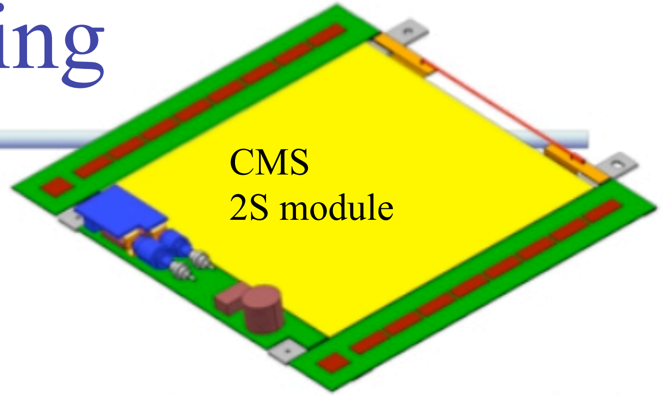


Measurement in ATLAS after full installation

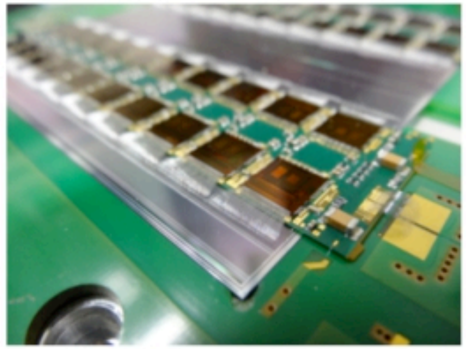
Needs to be measured in test beam AND magnetic field ….

- as cluster size, drift velocity and depletion voltage are depending on radiation damage this changes with the accumulated irradiation (fluence)

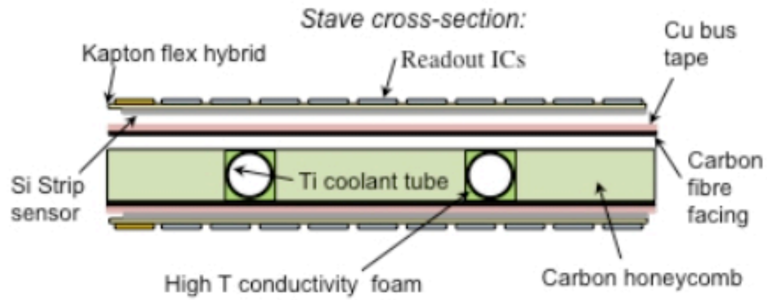
Next Generation Tracking

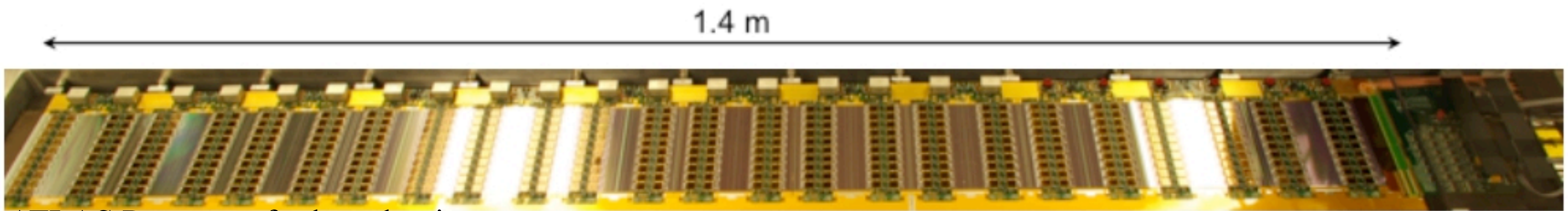


- ATLAS&CMS plan for ~200 m^2 silicon strip detector
- Commonalities:
  - 20000 modules to be produced
  - choice of sensor technology (n-- in-- p)
  - radiation level (10^{15} n_{eq}/cm^2)



- CMS:
  - modules discriminate low-- p_T tracks in the FE electronics
  - hybrid is key element: Wire-- bonds from the sensors to the hybrid on the two sides
- ATLAS:
  - stave concept where silicon is directly glued onto carbon fibre

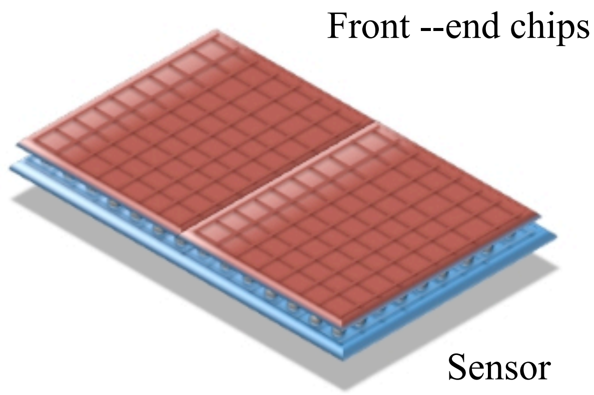




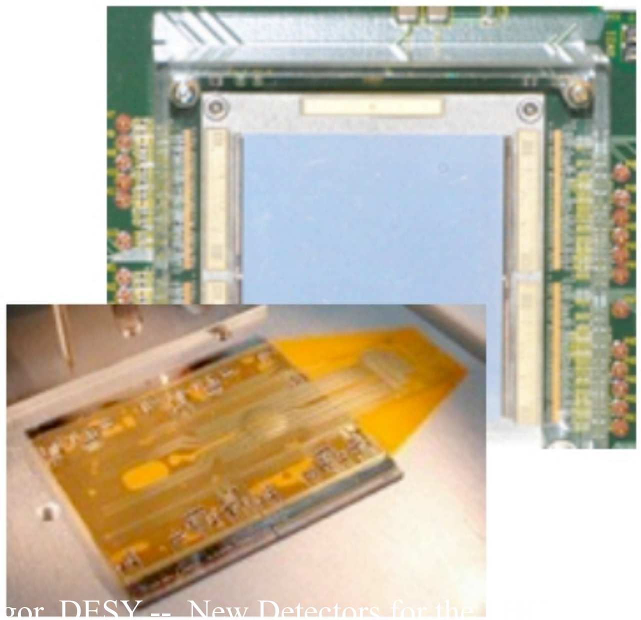
ATLAS Prototype for barrel strip stave

ATLAS and CMS Pixel Detectors

- The requirement of radiation tolerance is particularly demanding for the Inner Pixel:
  - ~16 x hit rates (occupancy)
  - 2-- 4 x better resolution needed (smaller pixel)
  - 10 x readout rates
  - >10 x radiation tolerance (new sensors and electronics needed)
  - increased forward coverage
  - less material ...
- Current pixel layout for ATLAS and CMS based on existing solutions
  - hybrid pixel approach with standard or novel sensors under investigation.
  - read-- out chips in 65 nm technology.
  - alternatives emerging
- **Several more years of R&D allow the use of more performant technologies.**

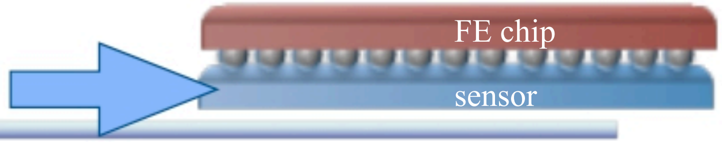


Hybrid pixel detector



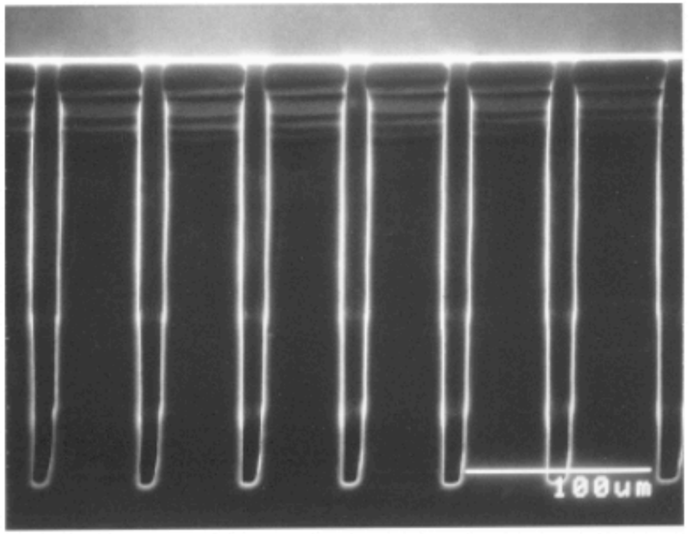
Example : ATLAS quad modules

New Technologies



3D Silicon

- Both electrode types are processed inside the detector bulk
- Charge collected by implants in pixels
  - max. drift and depletion distance set by electrode spacing
  - reduced collection time and depletion voltage
  - low charge sharing
  - lower leakage current and power dissipation
  - radiation tolerant
- First use case -- > ATLAS IBL



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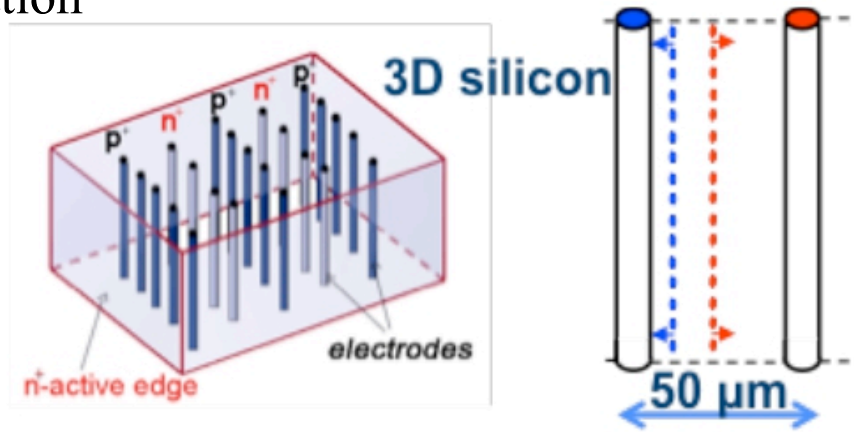
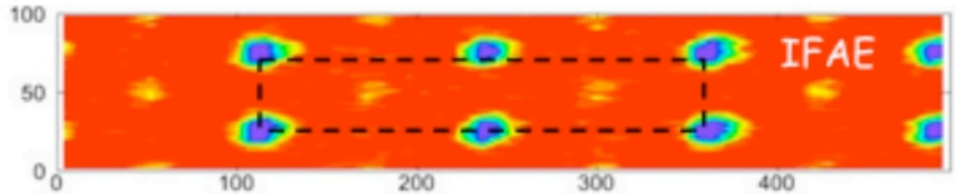
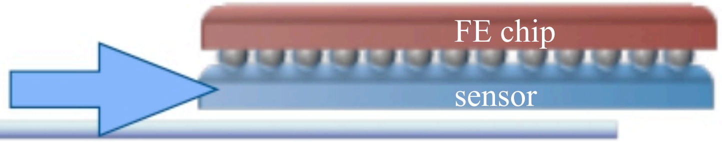




Efficiency measured at test

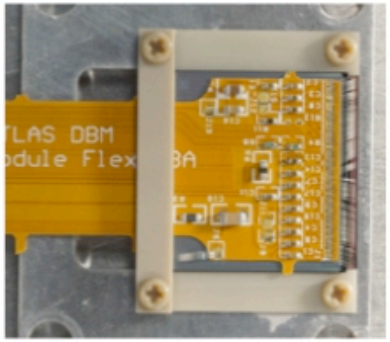
New Technologies

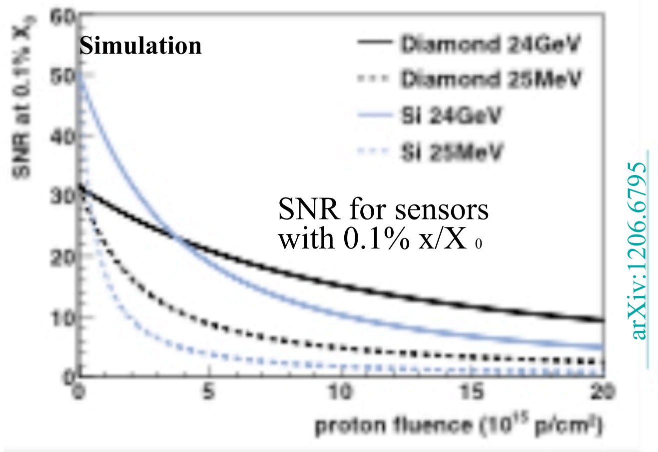


Diamond Sensors

- Chemical vapor deposition (CVD) diamond
  - band gap 5.5 eV (silicon: 1.1 eV)
  - displacement energy 42 eV/atom (silicon: 15 eV)
  - only 60% as many charge carriers as silicon
  - radiation tolerant
  - low Z

- Some issues:
  - availability (only two suppliers)
  - reduced charge collection after irradiation
  - difficulties with bump bonging

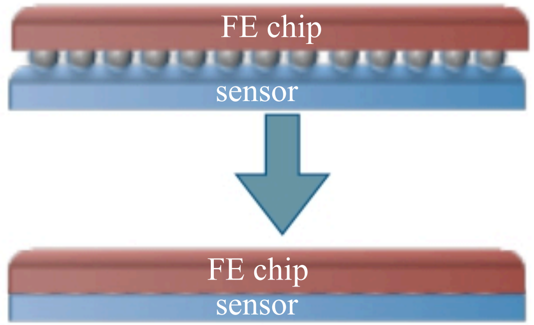




Future:
Combination of 3D and pCVD

New Alternative: CMOS

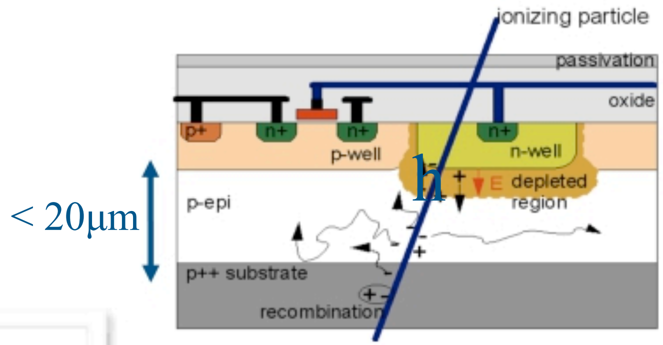
- Use of commercial CMOS technologies for replacement of sensor or even full hybrid (monolithic)
  - possible advantages: integration, cost, power consumption and material budget
  - currently in two experiments: DEPFET in Belle-- II and MAPS in STAR but only for moderate radiation suited



Monolithic = front --end electronics on same substrate as active sensor

- Classical CMOS sensors:
  - typically no backside processes
  - signal charge collection mainly by diffusion

  -- > moderate radiation tolerance (diffusion is suppressed by trapping < 10^{15} n_{eq}/cm^2)



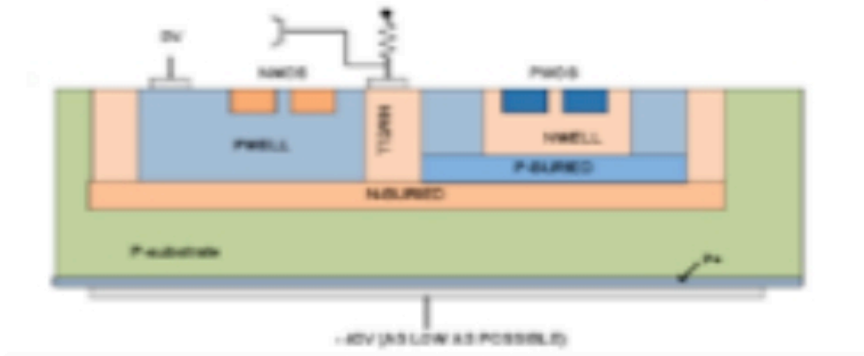
"Classic" CMOS sensor based on diffusion Mimosa

Main **challenge for HL-- LHC**: need combination of
- tolerance to displacement damage (depletion)
- integration of complex circuitry without efficiency loss
- keep using commercial technology

Grego

HR/HV CMOS

- HV/HR-- CMOS: in pixel collection electrodes plus readout circuitry
- Depletion either through high voltage (HV) or high resistivity substrate (HR)
- Charge is collected by drift, good for radiation tolerance
- But: risk of coupling circuit signals into input -- > careful design required
- Being followed up by ATLAS (pixels and strip);; CMS starting to look into it



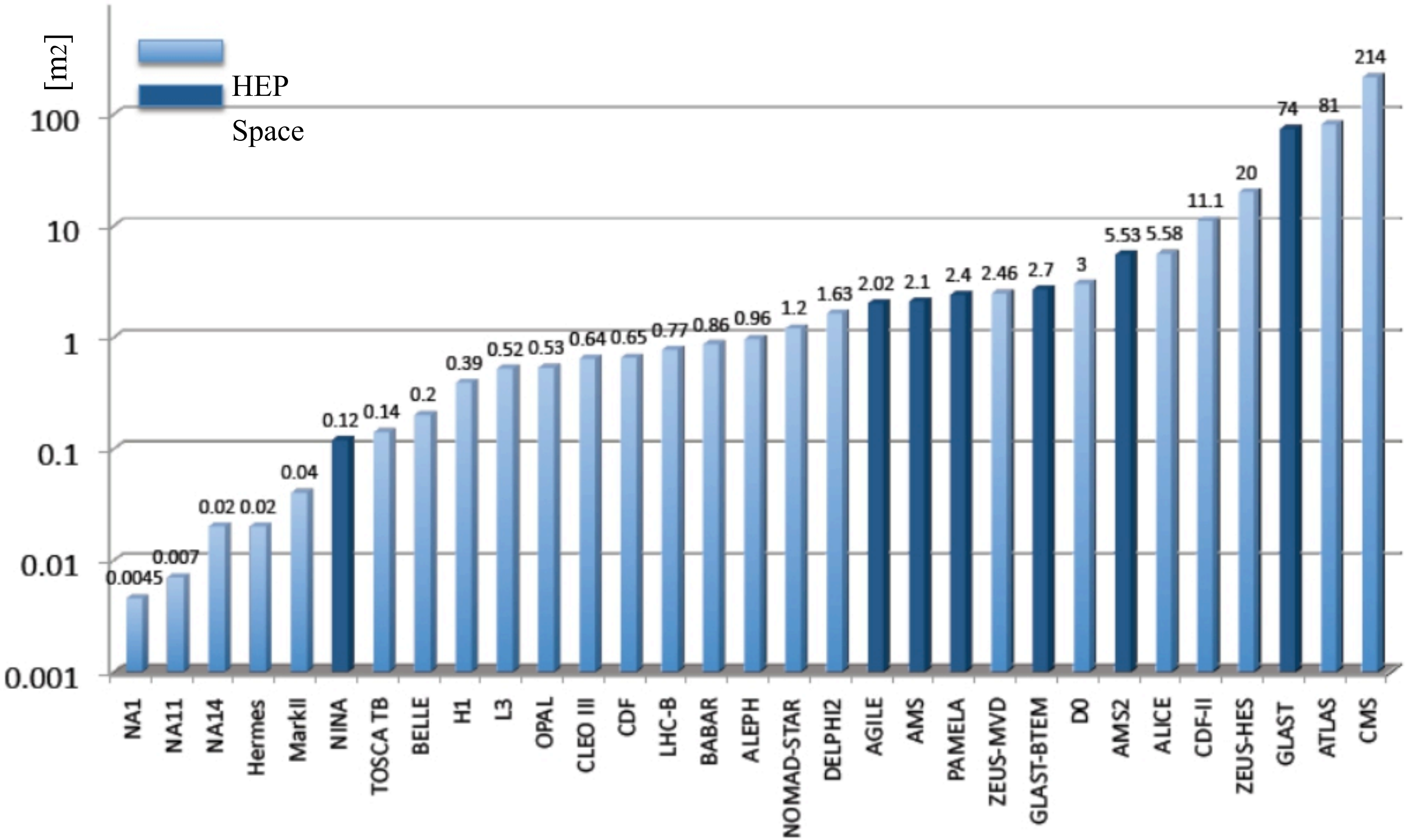
- Current results are **encouraging**
  - indication of good radiation tolerance
  - optimisation of signal and efficiency is one of next steps

Example:

A technology which could be used to build a **dream** tracker:

- fully monolithic but radiation hard
- high resolution
- thin material
- cost effective

Silicon detector size 1981 -- 2006



Summary

- Semiconductor detectors play a central role in modern high energy and photon physics
- Used in tracking detectors for position and momentum measurements of charged particles and for reconstruction of vertices (specially pixel detectors)
- By far the most important semiconductor: Silicon, indirect band gap 1.1 eV, however: 3.6 eV necessary to form e-h pair
- Advantages Si: large yield in generated charge carriers, fine segmentation, radiation tolerant, mechanically stable, …
- Working principle (general): diode in reverse bias (pn junction)
- Important : S/N has to be good. Noise ~1/C for systems that measure signal charge, smaller feature sizes are good. Pixel!
- Pixel detectors are used in most major current particle detectors and are planned for future experiment
- R&D for semiconductor detectors always has to be on the edge of technology