Detectors for High energy Physics

Part 3

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Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

IV. **Tracking Detectors**
- Semiconductor trackers
- Gas detectors
- Muon detectors

V. **Examples from the real life**

} ***Tuesday*** (III–IV)

} ***Wednesday*** (IV–V)

IV. Tracking Detectors

Tracking

- "tracking" in google image search:











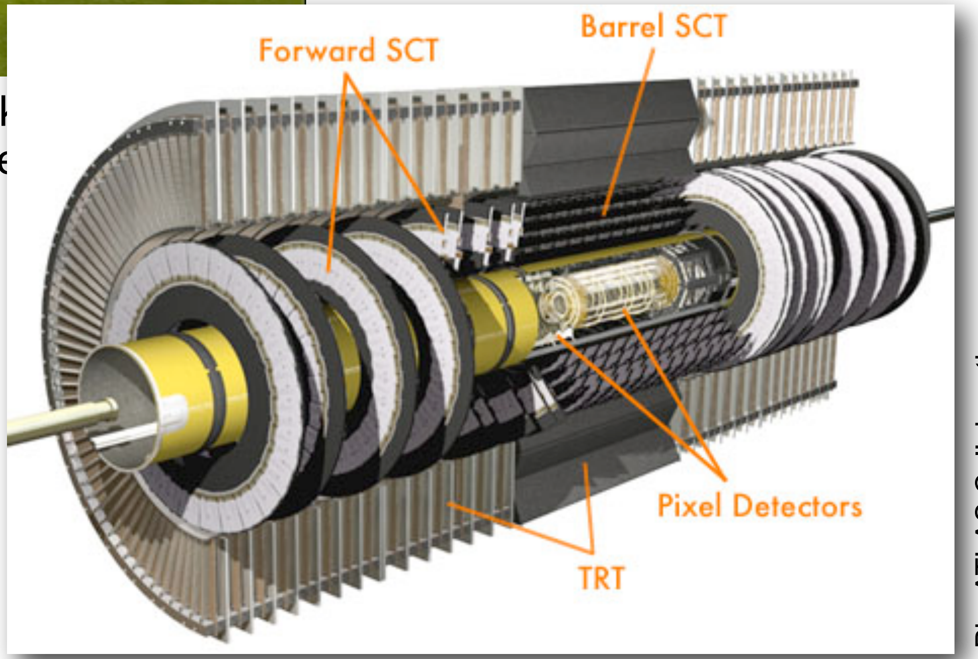

Tracking Detector

- “tracking detector” in google image search

GPS Tracking Detector

Online Multi-Person Track
from a Single, Uncalibrate

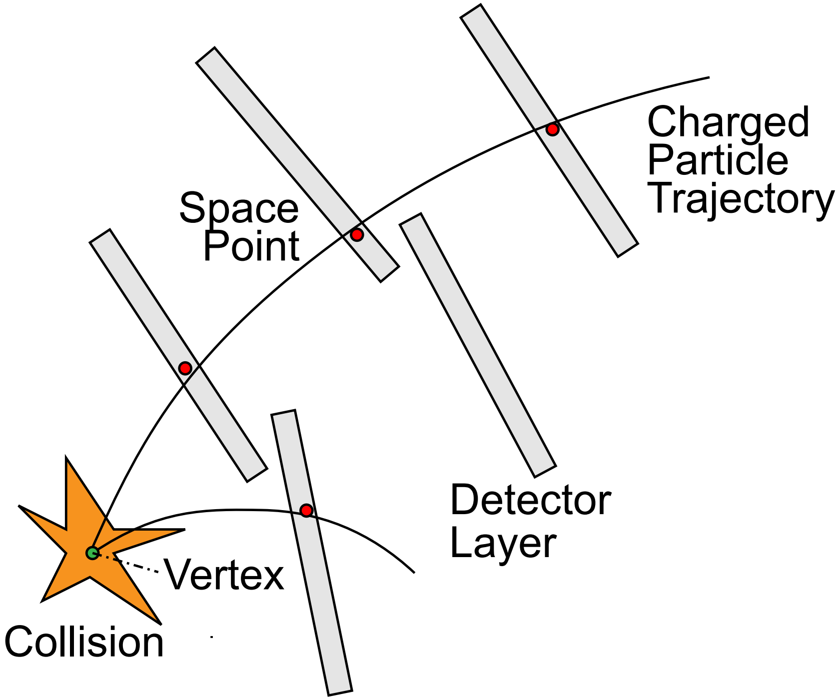
But the 1st image on list is:



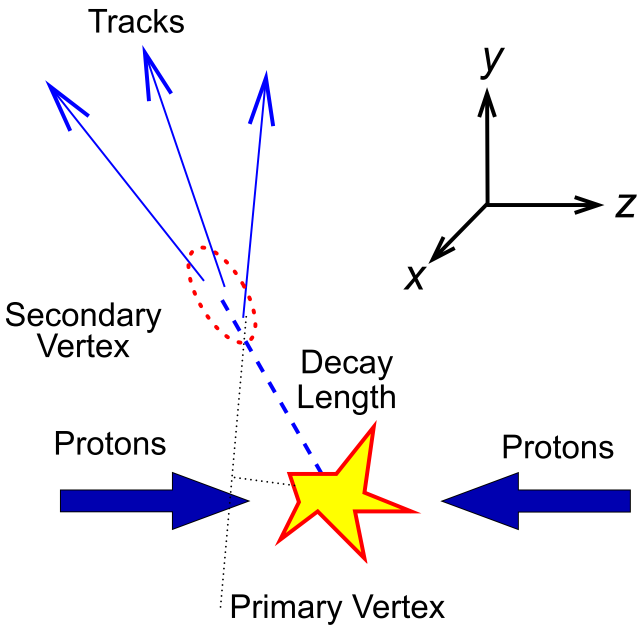
Pic: ATLAS Collaboration

Tracking Detectors

- Precise measurement of track and momentum of charged particles due to magnetic field.
- The trajectory should be disturbed minimally by this process (reduced material)



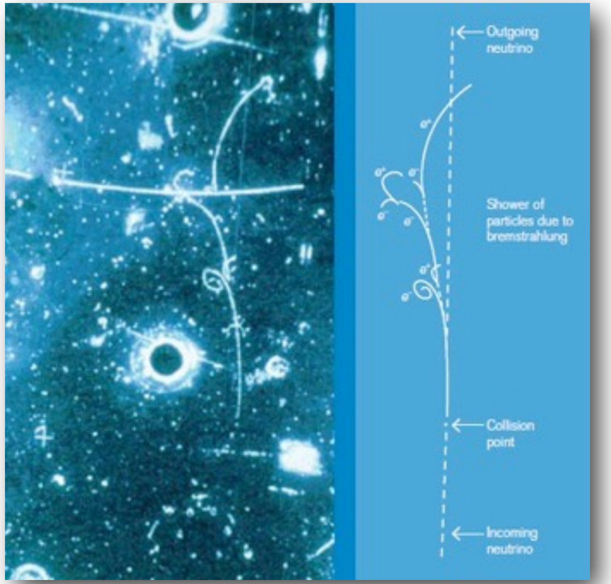
- Charged particles ionize matter along their path.
  - Tracking is based upon detecting ionisation trails.
  - An "image" of the charged particles in the event



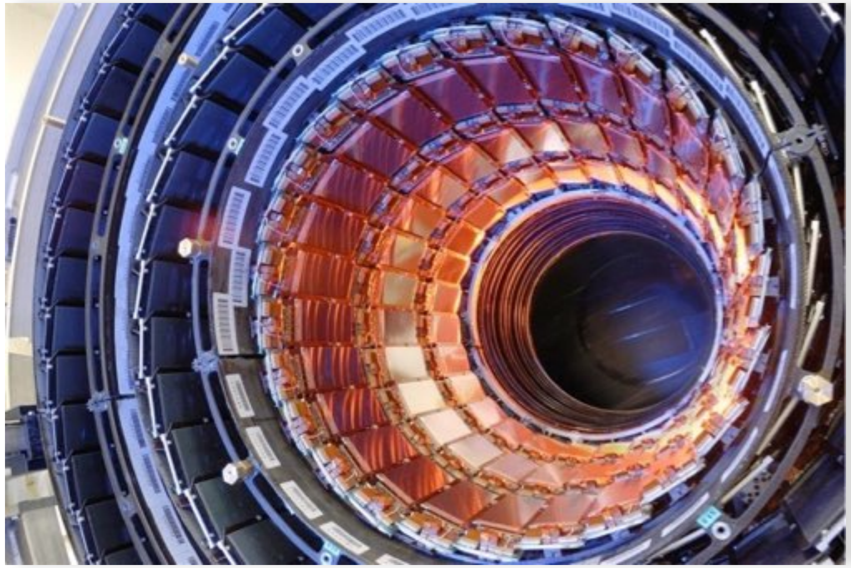
Pictures: U. Husemann

Tracking Detectors - Technologies

- **"Classic"**: Emulsions, cloud, and bubble chambers
  - Continuous media
  - Typically very detailed information but slow to respond and awkward to read out
- **"Modern":** Electronic detectors, wire chambers, scintillators, solid state detectors
  - Segmented
  - Fast, can be read out digitally, information content is now approaching the "classic" technology
  - Mostly used solid state detector -> Silicon (pixels and strips)



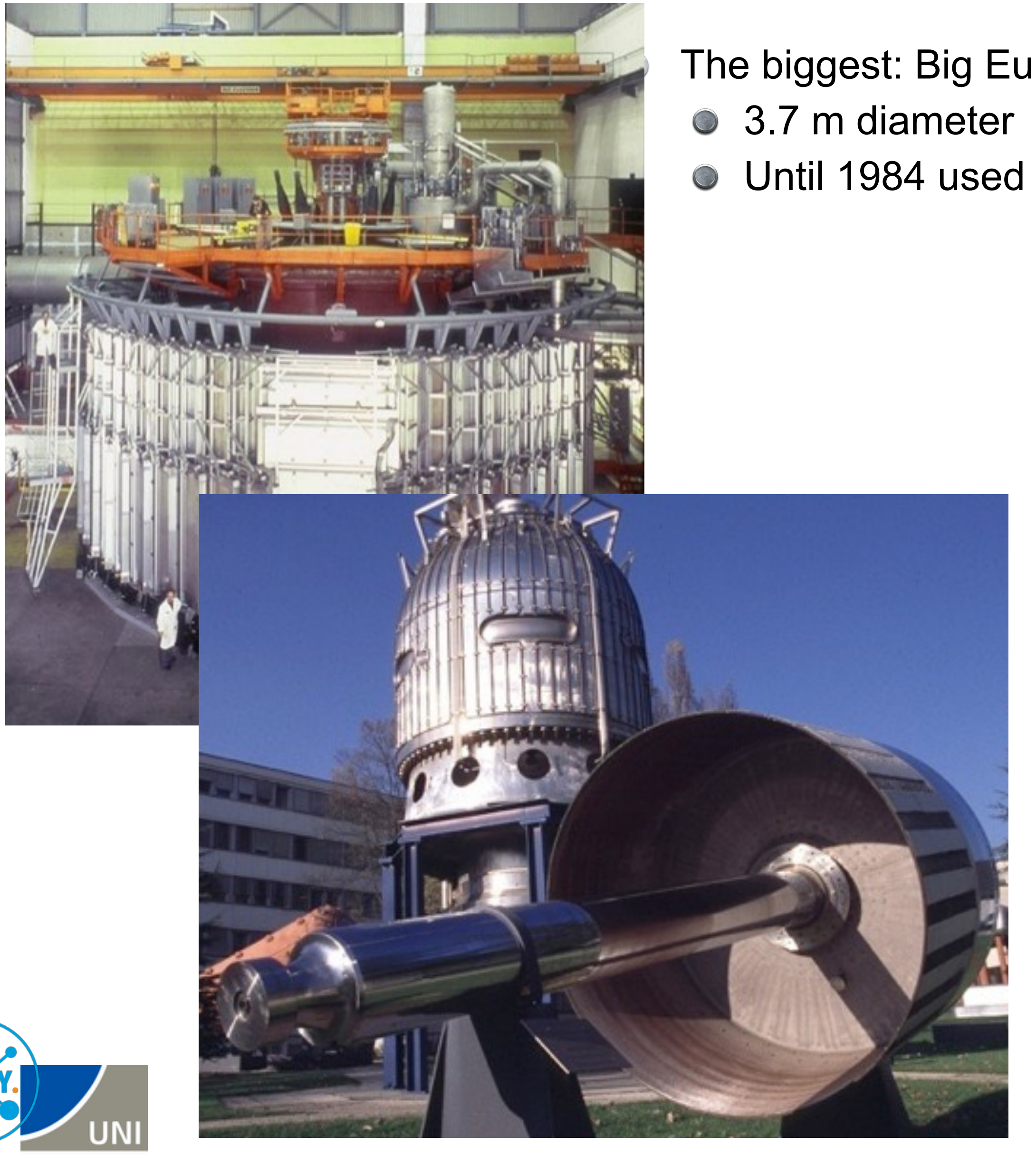
Discovery of neutral currents
Gargamelle, 1972



CMS Inner barrel Si Tracker:
Single-Sided Si-Strip

Pictures: CERN

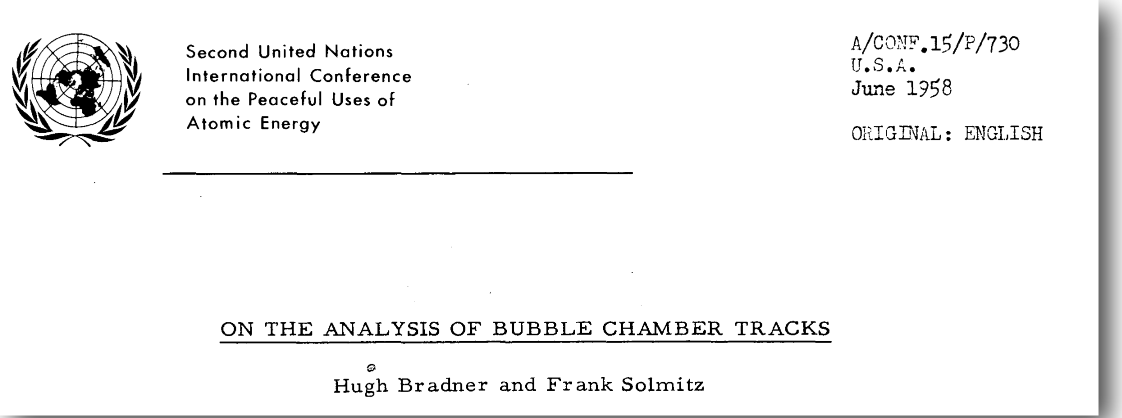
Very "Classic": Bubble Chamber



The biggest: Big European Bubble Chamber

- 3.7 m diameter
- Until 1984 used at CERN for the investigation of neutron hadron interactions

Early report on bubble chamber analysis:



Second United Nations
International Conference
on the Peaceful Uses of
Atomic Energy

A/CONF.15/P/730
U.S.A.
June 1958

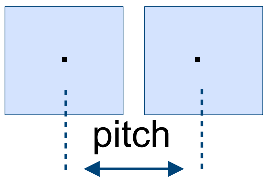
ORIGINAL: ENGLISH

ON THE ANALYSIS OF BUBBLE CHAMBER TRACKS

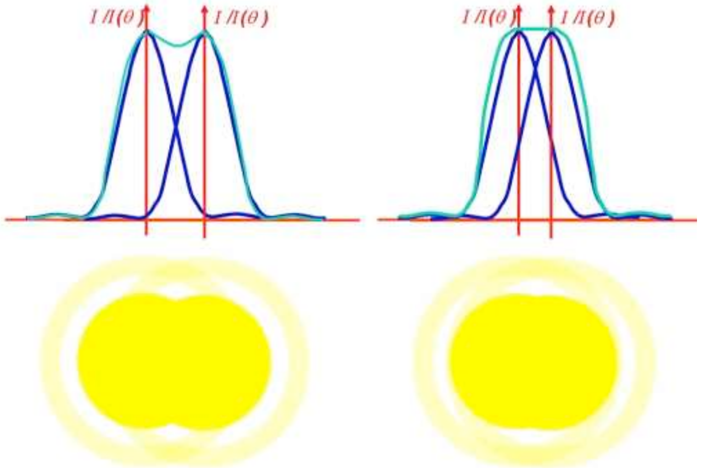
Hugh Bradner and Frank Solmitz

"… the large number of possible reactions, the variability of appearance of interaction, and the importance of being alert to possible new phenomena make it very important for a **trained physicist** to look at the bubble chamber pictures…."

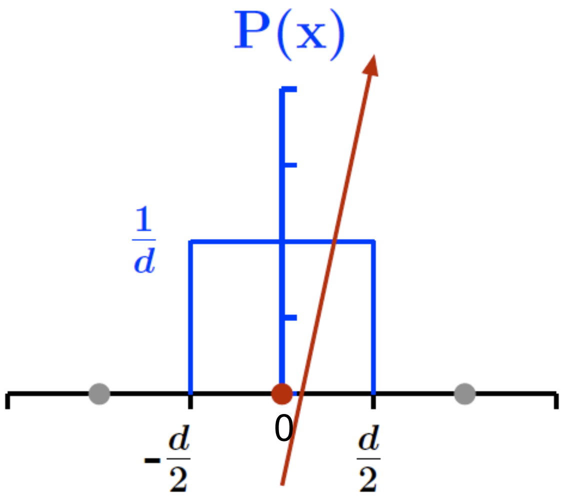
- An important figure of merit is the spatial resolution of a tracking detector
- Depending on detector geometry and charge collection
  - Pitch (distance between channels)
  - Charge sharing between channels



can be tubes, strips, wires, pixels ….



- Simple case: all charge is collected by one strip
- Traversing particle creates signal in hit strip (binary)
- 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:

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

Tracker: Important Parameter

- 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 (valid for tracking detectors with a pitch d):

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

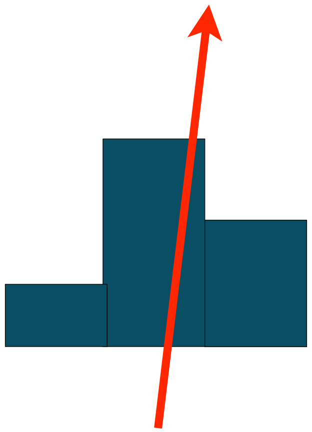
very important !

ATLAS/CMS Pixels

$\sigma_{r\phi} \approx 10\mu m$

- 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) and information about signal size
  - resolution improved by additional information of adjacent channels

$$\sigma \propto \frac{d}{(S/N)}$$



Tracking: Momentum in Magnetic Field

- A tracking detector is typically placed within a B-field to enable momentum measurements
- Charged particles are deflected in a magnetic field:
  - takes only effect on the component perpendicular to the field

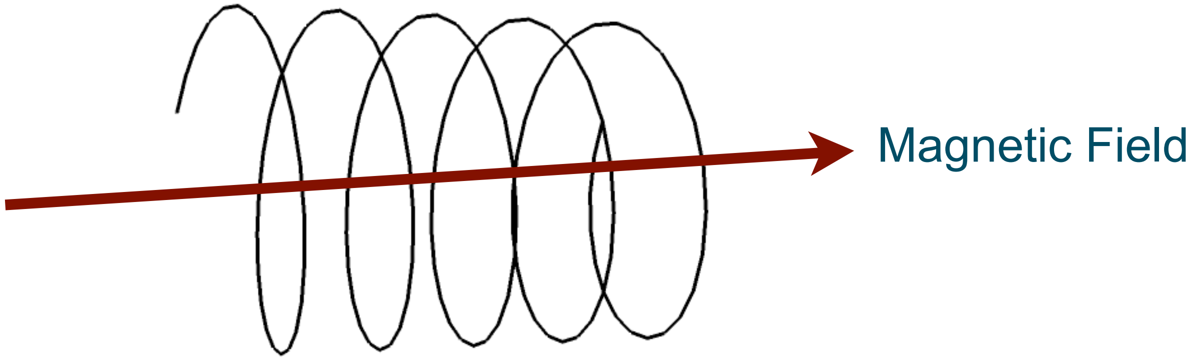
$$F = qvB$$
$$ma = qvB$$
$$m(\frac{v^2}{r}) = qvB$$
$$p = 0.3Br$$

Radius of the circular path is proportional to the transversal momentum

when converting in HEP units and assuming that all particles have the |electron charge|

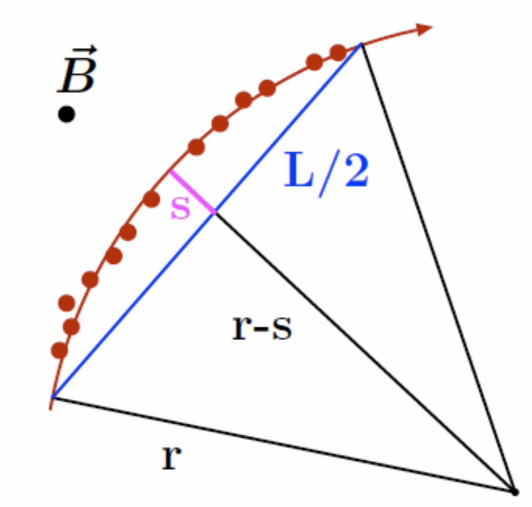
- parallel to the field is no deflection:

➫ particle is moving on a helix, the radius is determined by the field and p_T



Momentum in Magnetic Field II

- In real applications usually only slightly bent track segments are measured
  - Figure of merit: sagitta



Segment of a circle: $$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

$$\Rightarrow r = \frac{s}{2} + \frac{L^2}{8s} \approx \frac{L^2}{8s} \;(s \ll L)$$

With the radius-momentum-B-field relation: $$r = \frac{p_T}{0.3\,B} \Rightarrow s = \frac{0.3\,B\,L^2}{8\,p_T}$$

Momentum resolution due to position measurement:

Gluckstern $$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}$$

NIM, 24, P381, 1963

Momentum Resolution

- Precise measurement of track and momentum of charged particles due to magnetic field.
- The trajectory should be disturbed minimally by this process (reduced material)
  - Momentum resolution depending on many factors:

B = magnetic field
n = number of measurement points
L = length (~radius)
= spatial resolution

NIM, 24, P381, 1963

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}\right)^2 + \left(\frac{52.3\times 10^{-3}}{\beta B\sqrt{LL_y \sin\theta}}\right)^2 + (\cot\theta\sigma_\theta)^2$$

Position resolution — Multiple scattering — Angular resolution

The larger the magnetic field **B**, the length **L** and the number of measurement points **n**, and the better the spatial resolution, the better is the momentum resolution

For low momentum (β→0), multiple scattering will dominate the momentum resolution. Reduce material!

Angular resolution is usually not the most important term since θ_{min}»30-45° and σ_θ»10^{-3} rad.

When designing a tracking detector one should well understand what is required for the processes to be observed.

Ideal (non-realistic) tracking detector:
a massless, cheap, infinite granularity, 100% hermetic and efficient, infinite, long lifetime detector

Tracker: Important Parameter

- **Detector efficiency** ϵ: probability to detect a transversing particle
  - should be as close to 100% as possible
  - i.e. 12 layer silicon detector with 98% efficiency per layer -> overall tracking efficiency is only 78%
  - needs to be measured in test beam

$$\epsilon = \frac{N_{\text{meas}}}{N_{\text{exp}}}$$

ATLAS

$\epsilon_{\text{Pix}} > 97\%$ $\epsilon_{\text{Strips}} > 99\%$

$\epsilon = 0.99$ $\epsilon = 0.98$

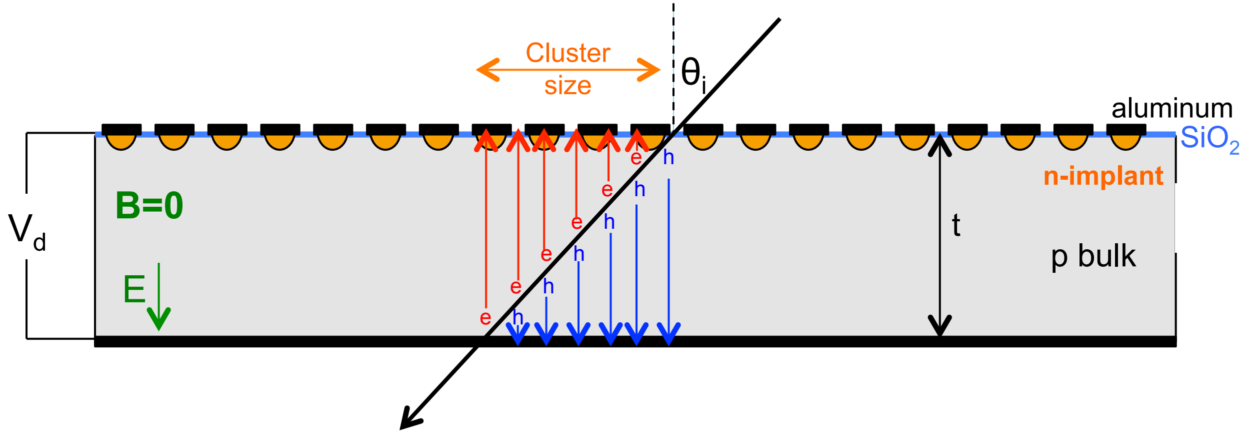
$\epsilon^7 = 0.93$ $\epsilon^7 = 0.87$

- **Track reconstruction efficiency:** how well a full track is reconstructed

$$\epsilon_{track} = \frac{N_{\text{inner}}}{N_{\text{muon}}}$$

$\epsilon_{\text{track}} > 95\%$

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



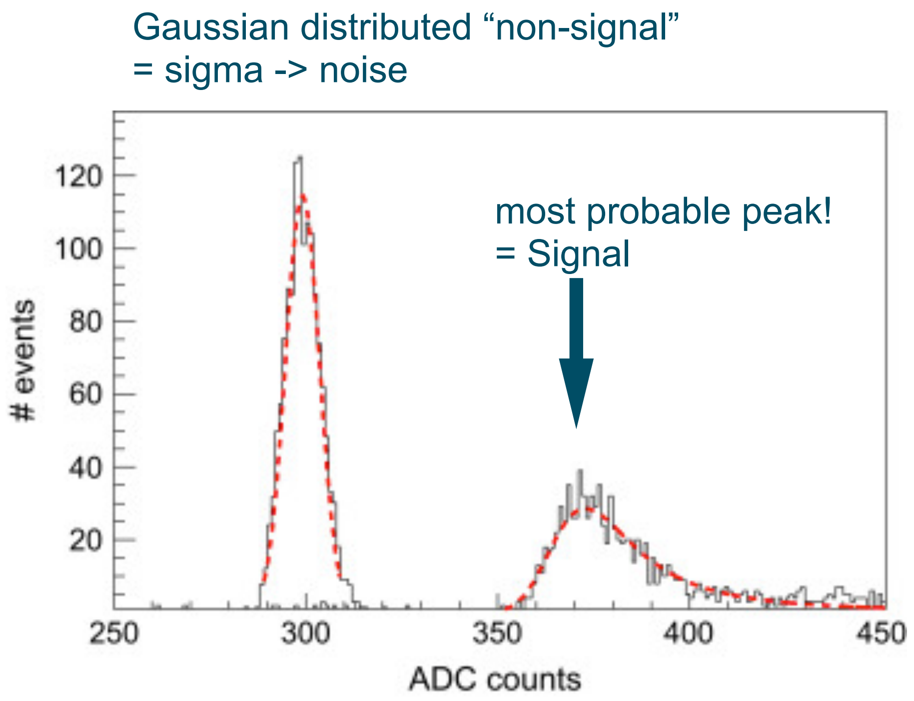
Tracker: Important Parameter

- **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 charge** needed
  - leakage current (ENC_I)
  - detector capacity (ENC_C)
  - det. parallel resistor (ENC_{Rp})
  - det. series resistor (ENC_{Rs})
  - signal induced by source or laser (or test beam particles)
  - optimal S/N for a MiP is larger than 20

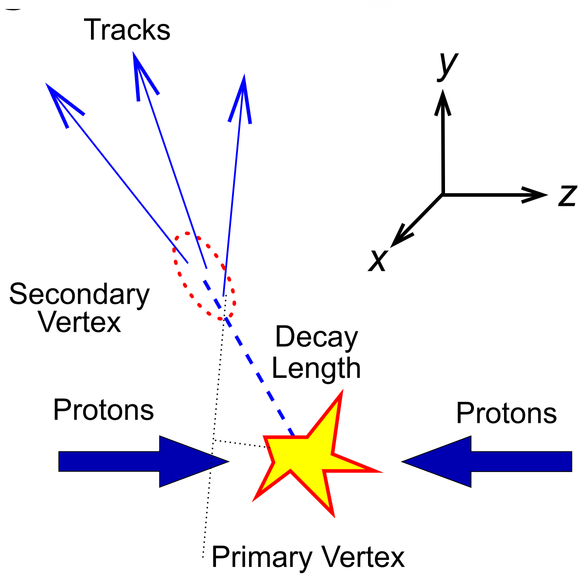
$$\mathrm{ENC} = \sqrt{\mathrm{ENC}_C^2 + \mathrm{ENC}_I^2 + \mathrm{ENC}_{R_p}^2 + \mathrm{ENC}_{R_s}^2}$$

example for silicon detector

With analog readout:



Impact Parameter Resolution



- Impact parameter resolution = shortest distance between the reconstructed track and the associated primary vertex

polar angle

$$\sigma_{r\phi}^2 = \sigma_{rz}^2 = a^2 + b^2 \cdot \frac{1}{(p \cdot sin^{\frac{3}{2}}\theta)^2}$$

intrinsic resolution of the tracking system (no multiple scattering)

influence of multiple scattering (geometry)

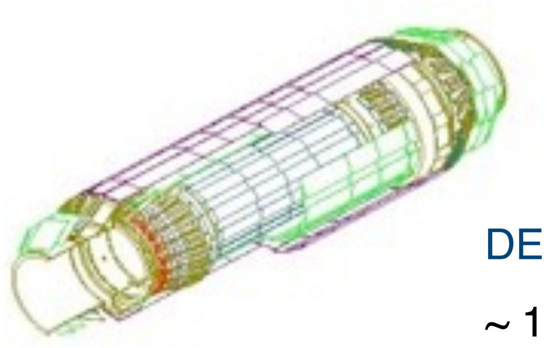
Accelerator	a (μm)	b (μm)
LEP	25	70
SLD	8	33
LHC	12	70
RHIC-II	13	19
ILC/CLIC	<5	<15

ATLAS $\sigma_{\mathrm{IP}} > 10\mu m$ for 100GeV track

IV.A Semiconductor-Detectors

Large Silicon Systems

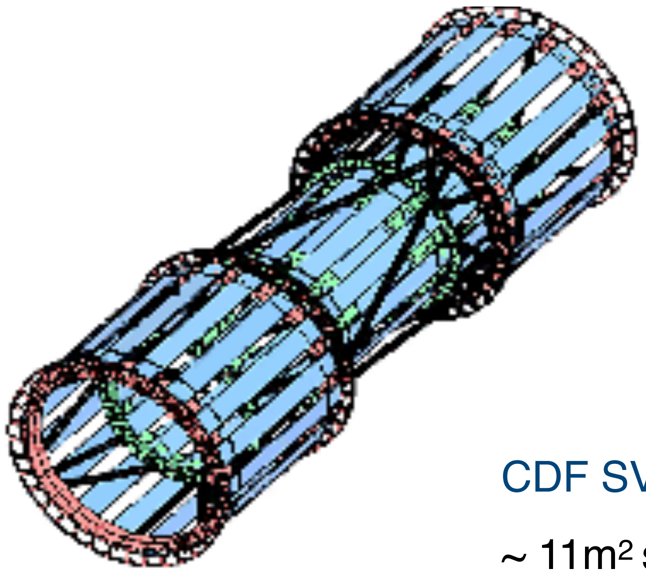
Since ~ 30 years: Semiconductor detectors for precise position measurements.



DELPHI (1996)

~ 1.8m² silicon area

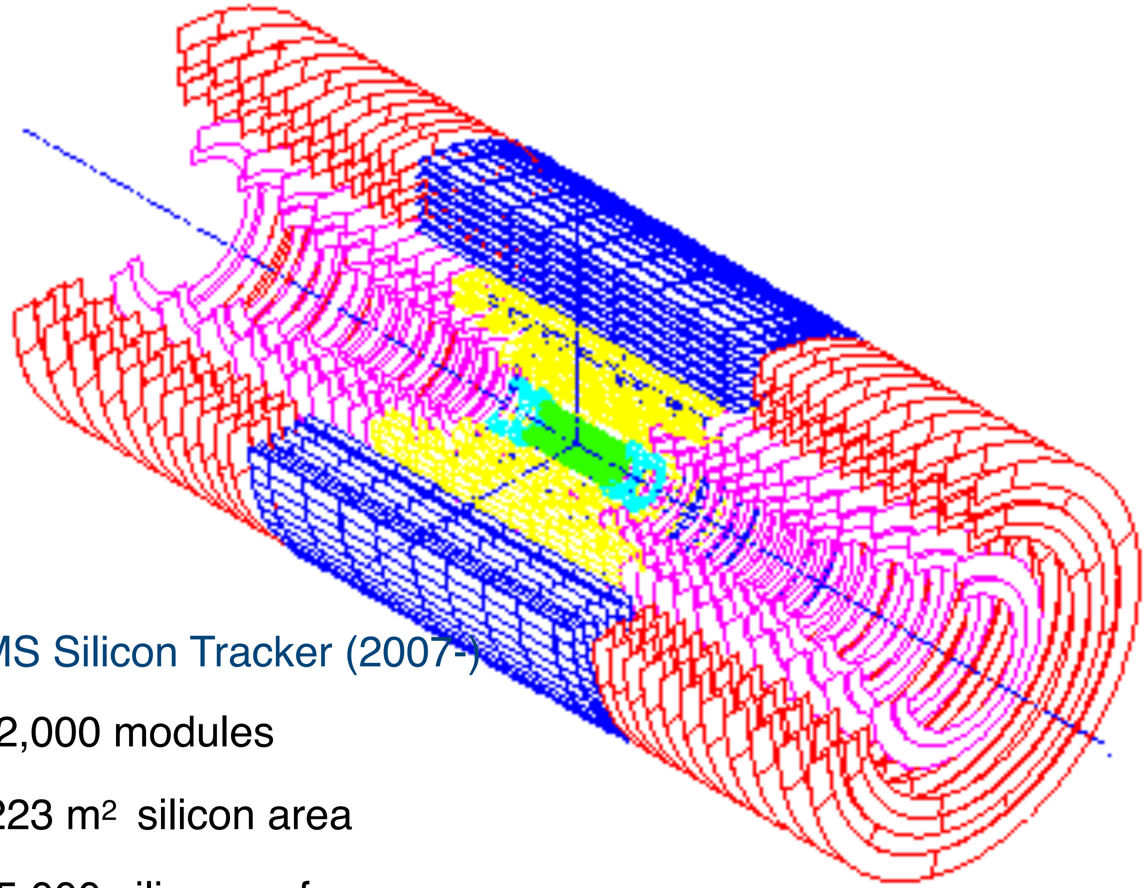
~ 175 000 readout channels



CDF SVX IIa (2001-2012)

~ 11m² silicon area

~ 750 000 readout channels



CMS Silicon Tracker (2007-)

~12,000 modules

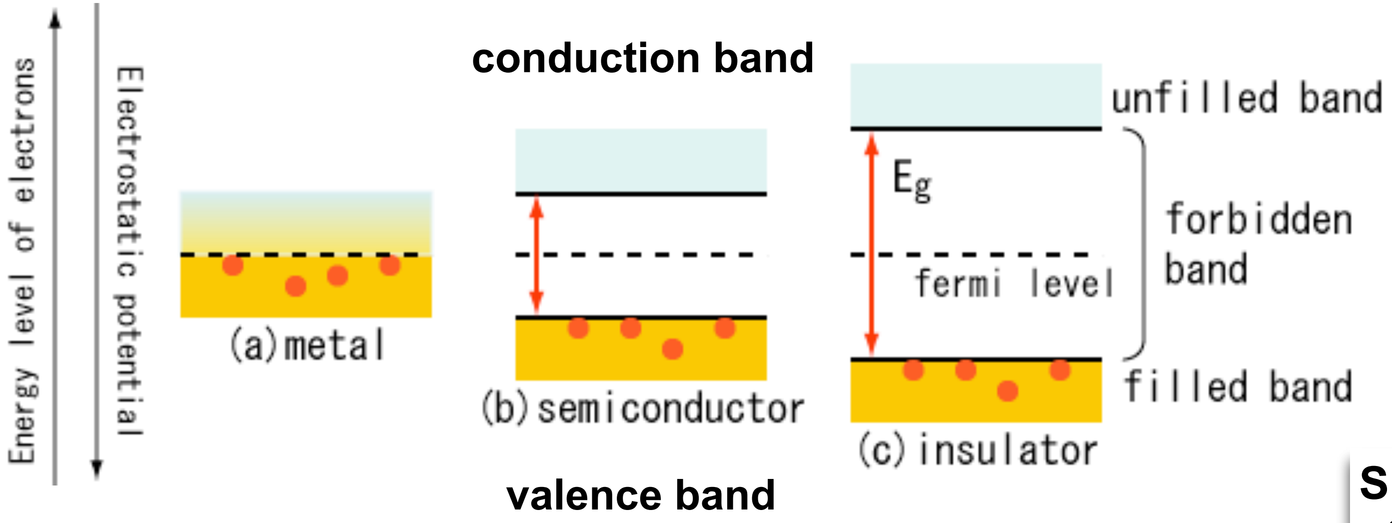
~ 223 m² silicon area

~25,000 silicon wafers

~ 10M readout channels

Semiconductor Basics

- In free atoms electron energy levels are discrete.
- In a solid, energy levels split and form a nearly-continuous band.

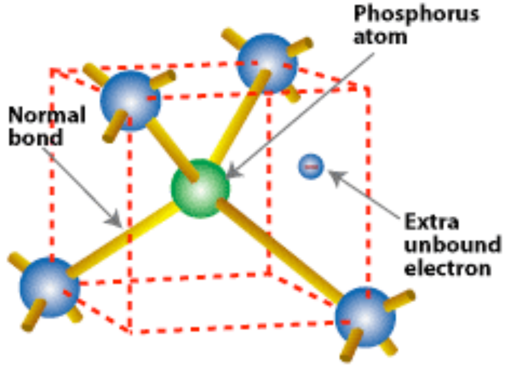


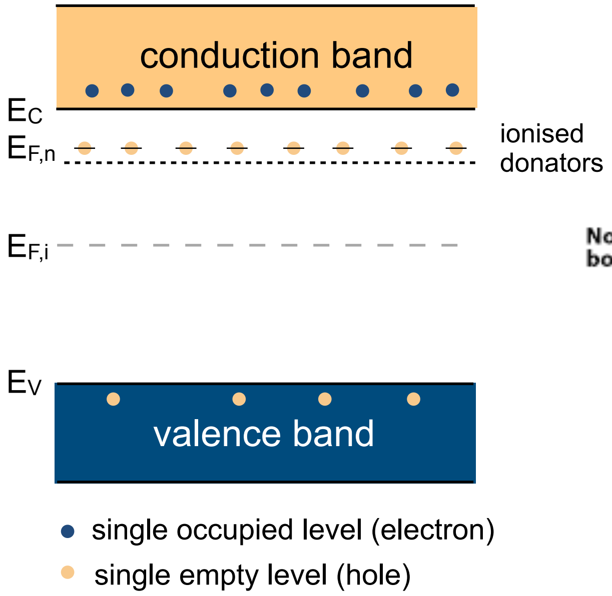
- Large gap: the solid is an insulator.
- No gap: it is a conductor.
- Small band gap: semiconductor

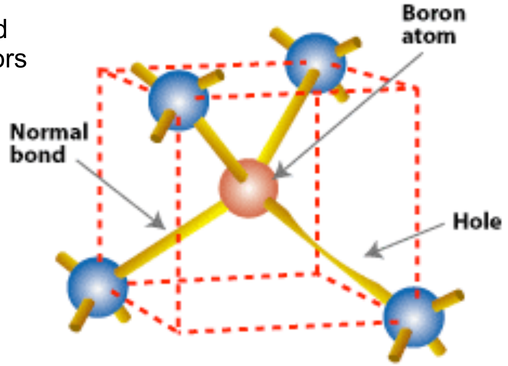
Signal of charged particle:
~3 x 10^4 electron/hole pairs
Intrinsic charge carrier
~4 x 10^8 electron/hole pairs
300µm

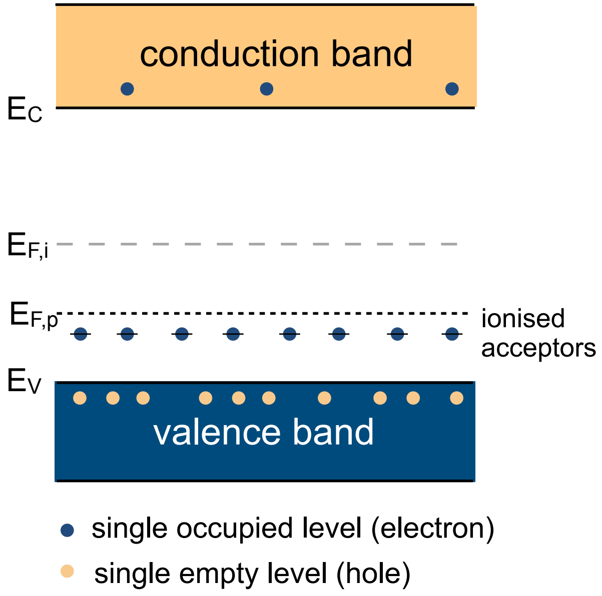
- For silicon, the band gap is 1.1 eV, but it takes 3.6 eV to ionise an atom
  - Remaining energy goes to phonon excitations (heat).

Doping Silicon









n type semiconductor:

- Negative charge carriers (electrons) by adding impurities of donor ions (e.g. Phosphorus (type V))
- **Donors** introduce energy levels close to conduction band thus almost fully ionised (E_F closest to CB)

Electrons are the majority carriers.

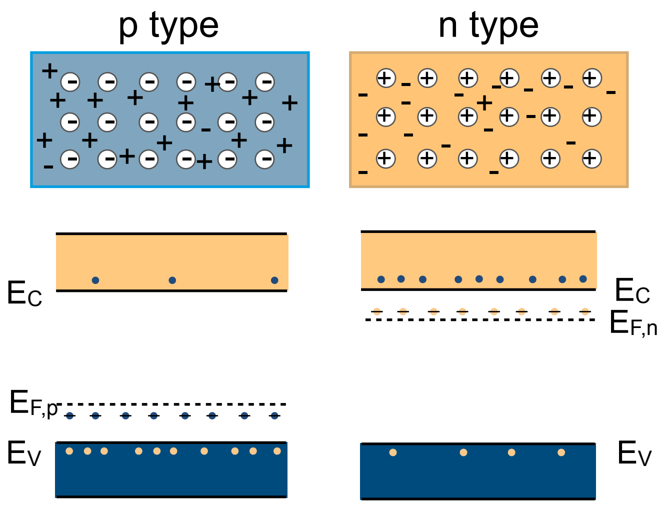
p type semiconductor:

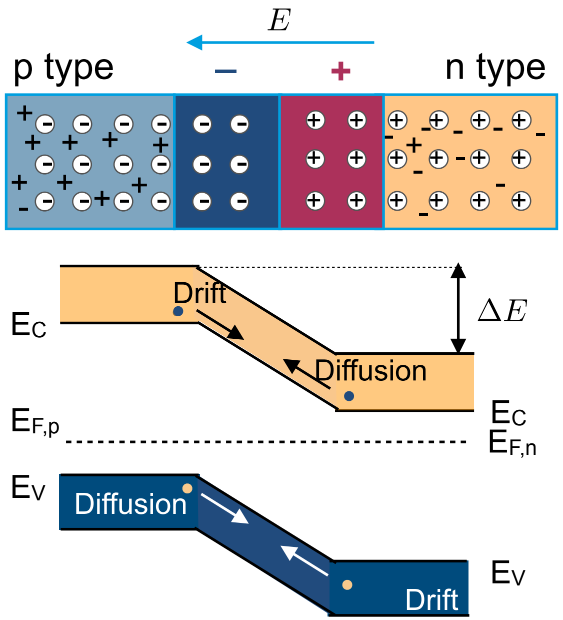
- Positive charge carriers (holes) by adding impurities of acceptor ions (e.g. Boron (type III)).
- Acceptors introduce energy levels close to valence band thus 'absorb' electrons from VB, creating holes (E_F closest to VB).

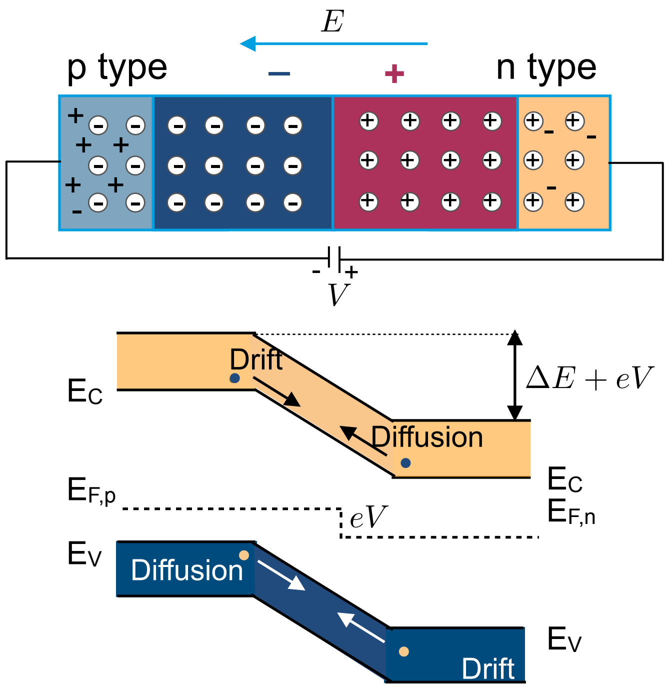
Holes are the majority carriers.

Basis of Silicon Detector: PN Junction

- At interface of p type and n type semiconductor difference in the Fermi levels causes diffusion of excessive carriers to the other material until thermal equilibrium is reached.
- Stable space charge region free of charge carriers is called **depletion zone**.
- Typical current-voltage of a p-n junction: exponential current increase in forward bias, small saturation in reverse bias.







Applying an external voltage V with the cathode to p and the anode to n (reverse biasing), e-h pairs are pulled out of the depletion zone. ➔ **larger depletion zone** ➔ suppress current across the junction

pn-junction with reverse bias

Principle of Semiconductor Detectors

- Creation of electric field: voltage to deplete thickness d

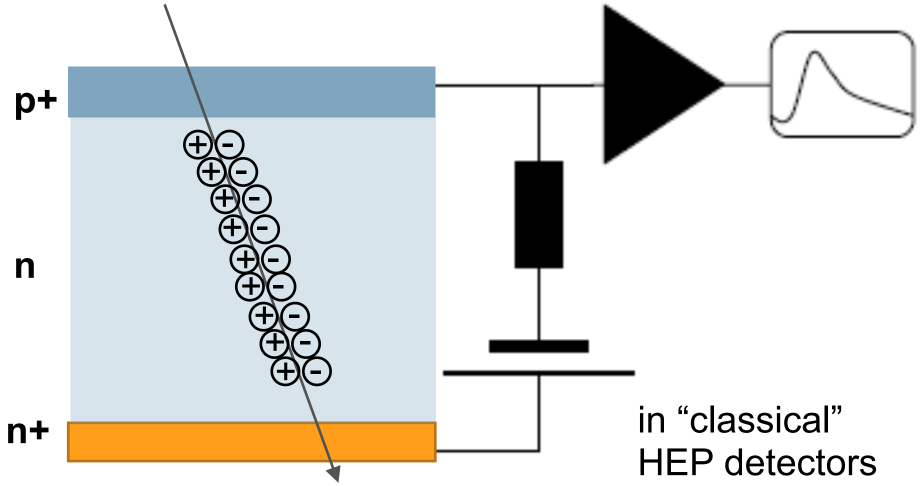
with $n_A >> n_D$

$$d = \sqrt{\frac{2\epsilon\epsilon_0 V_{dep}}{e n_D}}$$

for $d = 300\mu m$: $V_{dep} \approx 160V$

- Passage of a charged particle: Electron-hole pairs formed in the depletion zone
  - Drift under the influence of the electric field
  - Signal depends on width of depletion zone

> The signal is induced by the motion of charge after incident radiation (not when the charge reaches the electrodes).



in "classical" HEP detectors d=100-300 μm

Typical numbers

Doping concentration

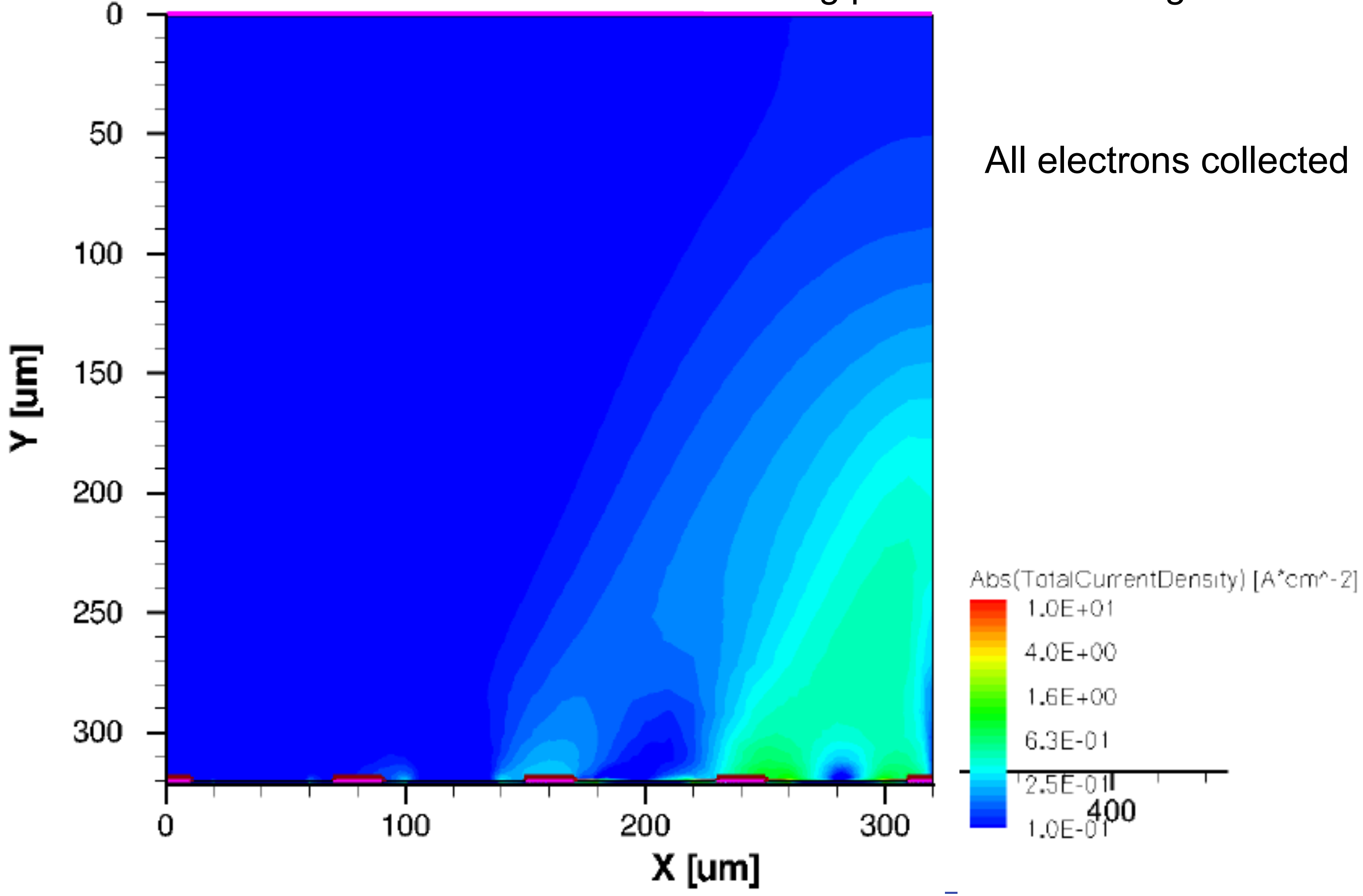
$n_A \approx 10^{19} cm^{-3}$ Acceptors

$n_D \approx 2 \cdot 10^{12} cm^{-3}$ Donators

Current Density

Ionizing particle with 45° angle t=7ns

All electrons collected



Simulation: Thomas Eichhorn

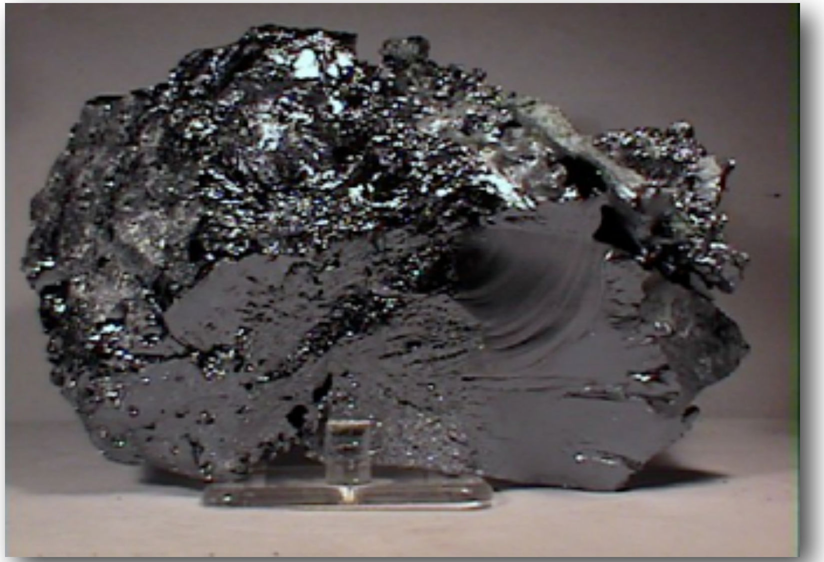
Material Properties

	Si	Ge	GaAs	CdTe	Diamond	SiC
band gap	1.12	0.67	1.42	1.56	5.48	2.99
energy for e-p pair [eV]	3.6	2.9	4.2	4.7	13.1	6.9
e- for MIP (300µm)	24000	50000	35000	35000	9300	19000
Z	14	32	31+33	48+52	6	14+6

Why is silicon used more often ?

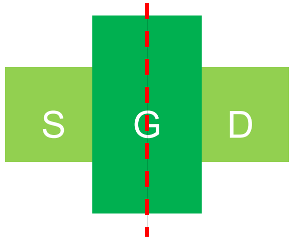
- Silicon is the only material which can be produced in larger areas in high quality

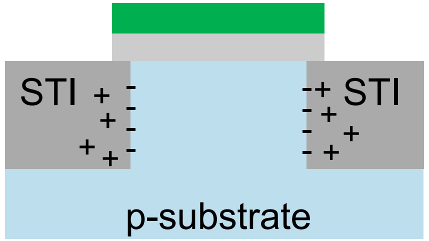
- compare to kT = 0.026 eV at room temperature -> dark current under control
- high density compared to gases: ρ=2.33g/cm³
- good mechanical stability -> possible to produce mechanically stable layers
- large charge carrier mobility
- fast charge collection δt~10ns
- well understood -> radiation tolerant



Problem: Radiation Damage

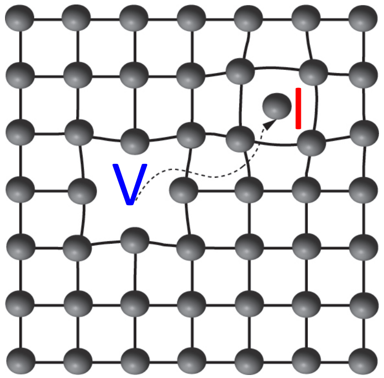
- Radiation damages the silicon on atomic level significantly leading to macroscopic effects.
- **Surface effects:** Generation of charge traps due to ionising energy loss — Total ionising dose, TID **(problem for sensors and readout electronics).**
  - Cumulative long term trapping of positive charge
  - Increase of leakage current and oxide breakdown





STI = shallow trench interface

- **Bulk effects:** displacement damage and build up of crystal defects due to non ionising energy loss (NIEL) **(main problem for sensors).**
  - Unit: 1MeV equivalent n/cm^2



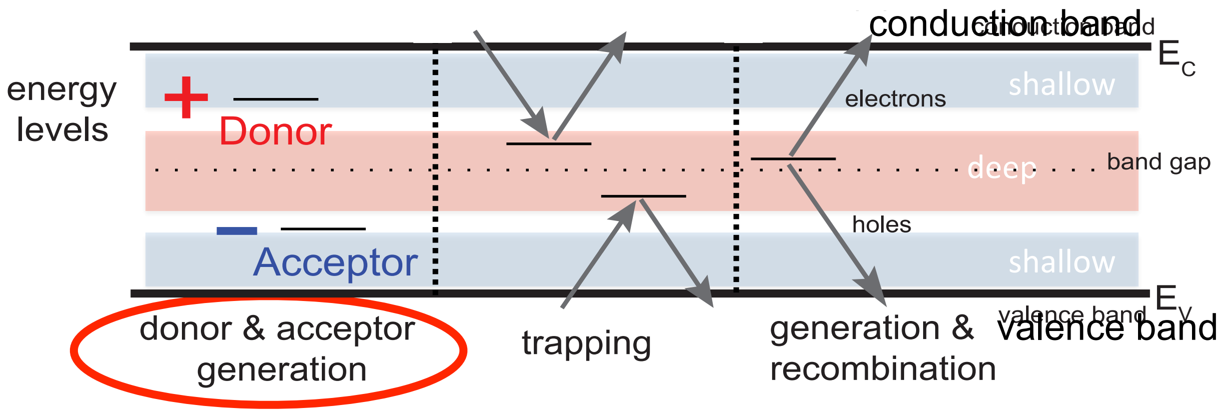
Defects composed of:
Vacancies and Interstitials

Compound defects with impurities possible!

Detector	NIEL [1MeV n_{eq}/cm^2]	TID [Mrad]
ALICE ITS	10^{13}	<1
Belle II (per year)	1.2×10^{13}	1.9
ATLAS/CMS Outer Tracker	10^{15}	<100
ATLAS/CMS Inner Tracker	10^{16}	1000

Radiation Damage: Macroscopic Effects

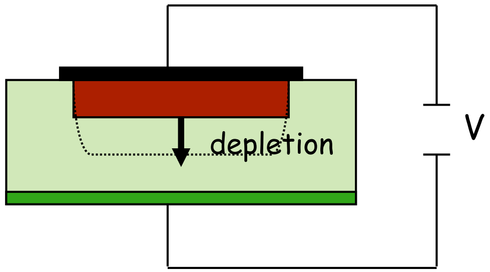
- Impact of defects on detector properties depends on defect level in band gap



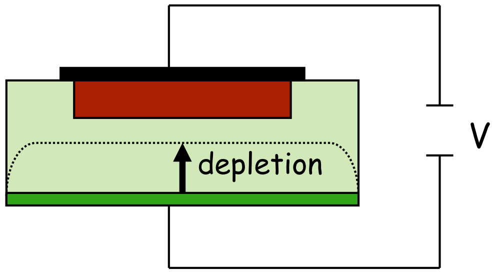
Donor&acceptor generation:
Change of effective doping concentration (N_{eff})

$$V_{dep} = d^2 N_{eff} \frac{q}{e\epsilon\epsilon_0}$$

- Increase of depletion voltage
- Under-depleted operation



Before type inversion

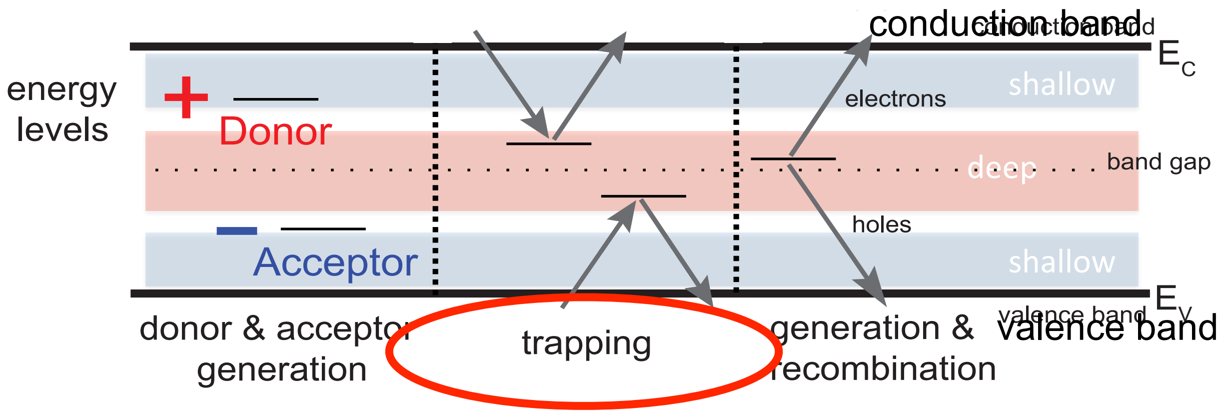


After type inversion

M. Moll, PhD thesis, Uni Hamburg 1999

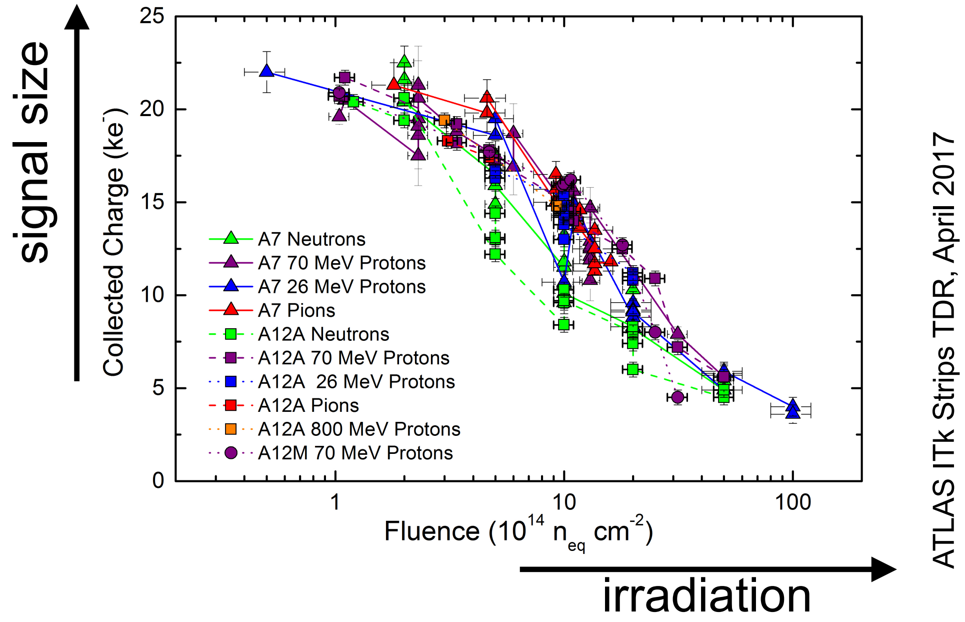
Radiation Damage: Macroscopic Effects

- Impact of defects on detector properties depends on defect level in band gap



Increased charge trapping

Lower signal (less charge)
Reduced charge collection efficiency



Radiation Damage: Macroscopic Effects

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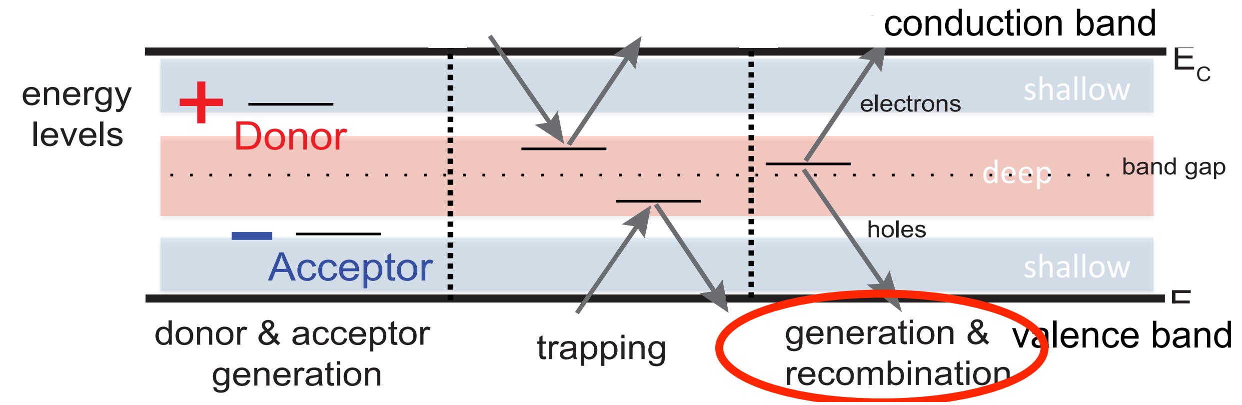
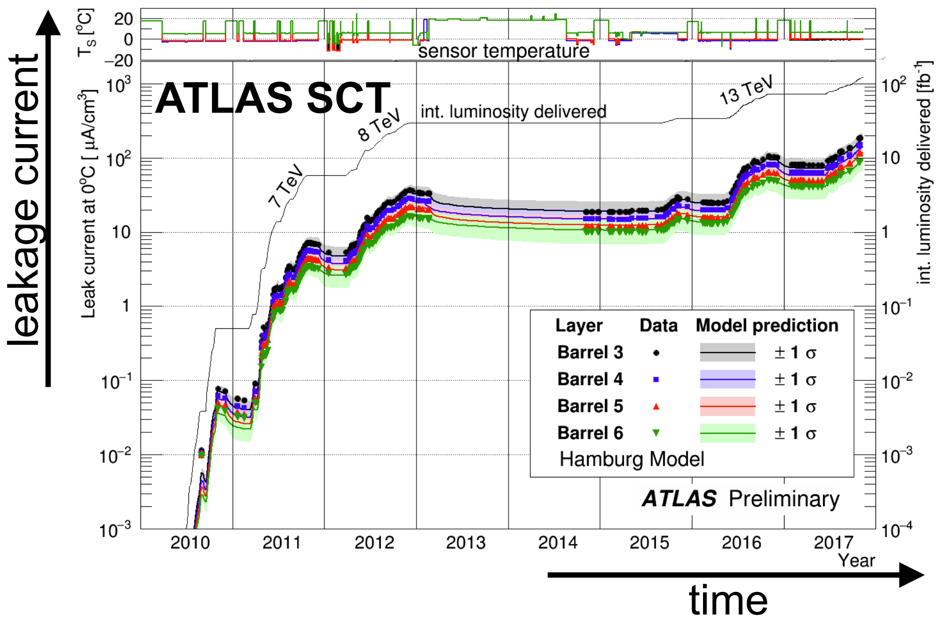
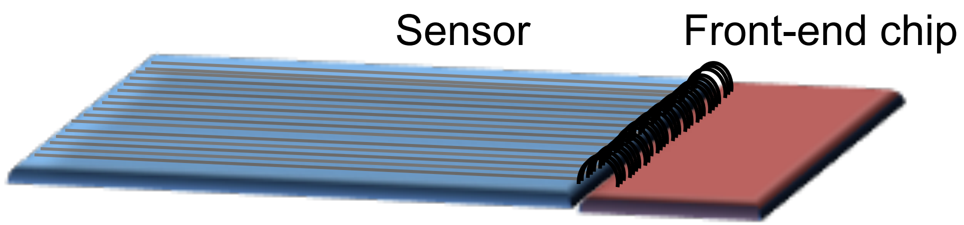


Increase of leakage current
higher shot noise; thermal runaway
→ Cooling during operation helps
(leakage current depends on T)



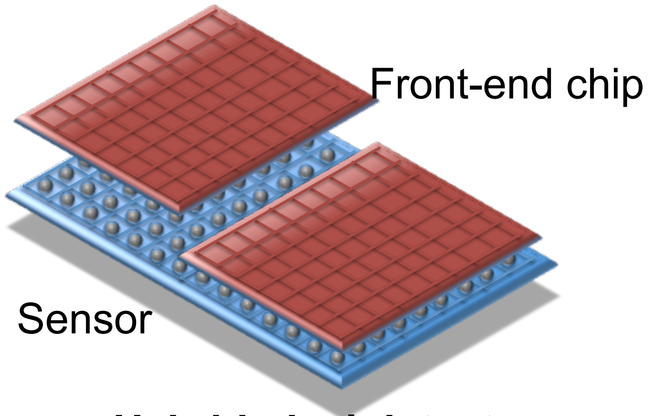
Strips and Pixels

- **Strips detector:** charge sensed by long narrow strips 1D information (typically 20 - 100µm)
  - 2D information by double sided processing or adding back to back second layer slightly rotated (stereo angle)
- In regions with higher track density one dimensional measurements can lead to ambiguities.

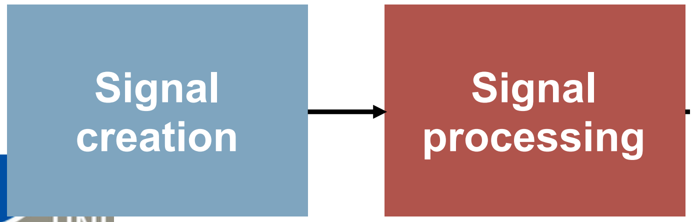


Microstrips detector

- **Pixel detector:** charge sensed by small pixels on one side of sensor
  - Hybrid pixels: sensors and readout joined via bump bonds
  - Monolithic pixels: sensor and readout on one substrate



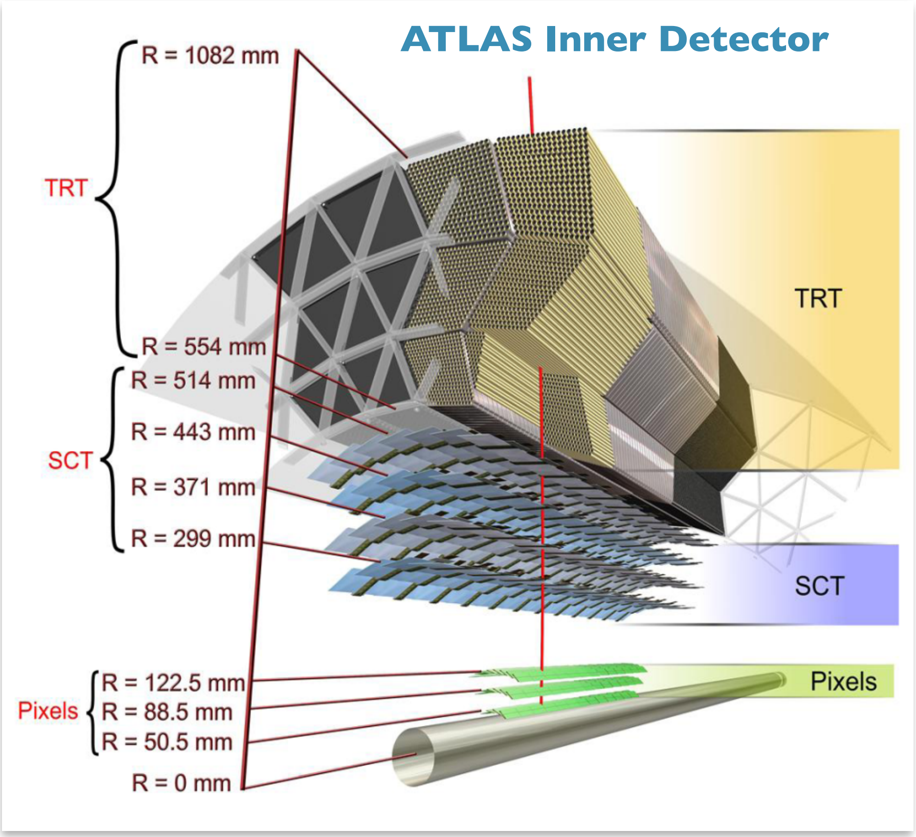
Hybrid pixel detector

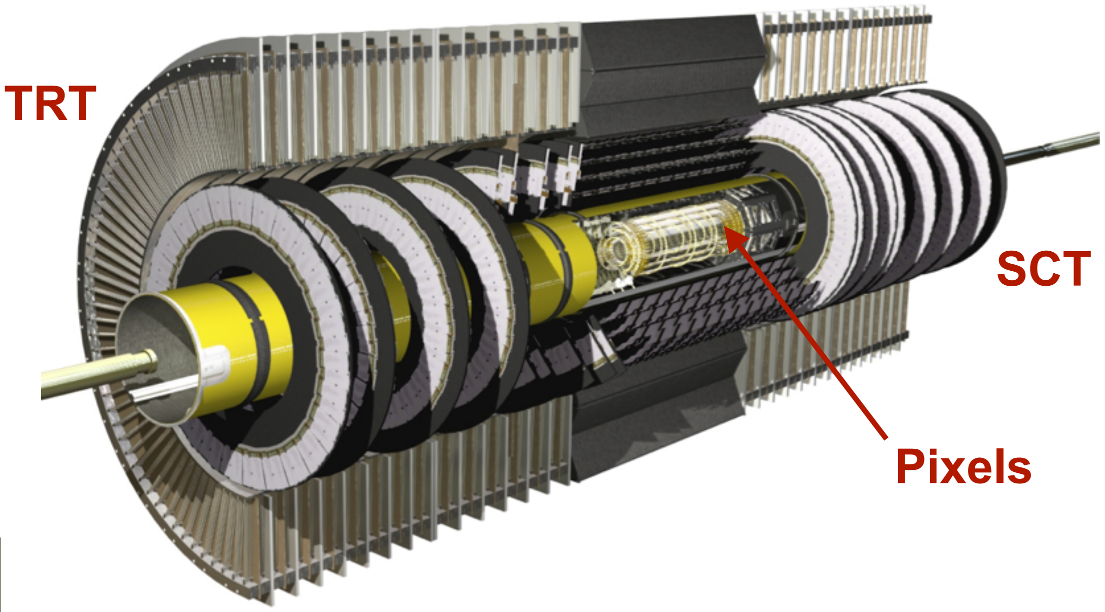


- Signals created in silicon by charged particle
  - Very small signals (fC): need amplification
  - Measurement of amplitude/hit and/or time (ADCs, discriminators, TDCs)
  - Several thousands to millions of channels

Example: Current ATLAS Silicon Detector

- Current tracking detector “the first meter”:
  - Silicon pixel detector
    - 4 layers, 8 disks
    - Pixel size: 50 x 400µm² (IBL: 50 x 250µm²)
    - 2000 modules with 140M channels
  - SemiConductor Tracker (SCT)
    - Strips width: 70µm
    - 4088 modules with 6.3M channels, 62m²

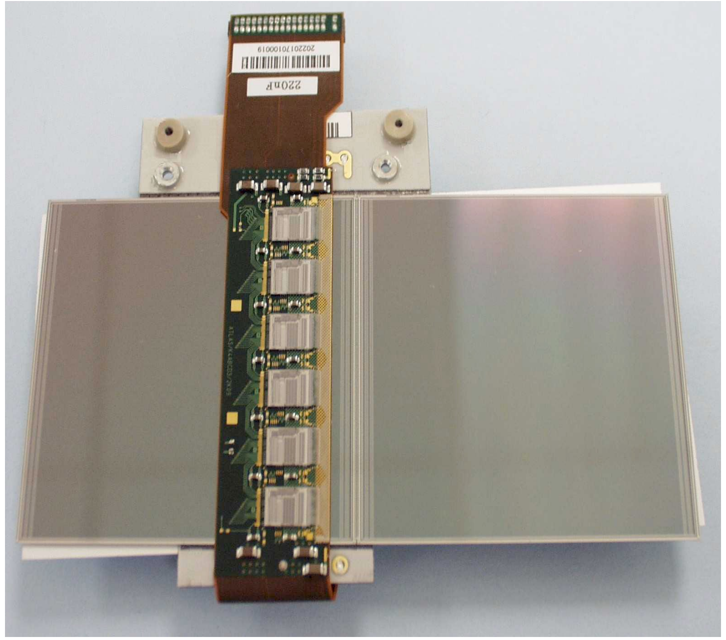


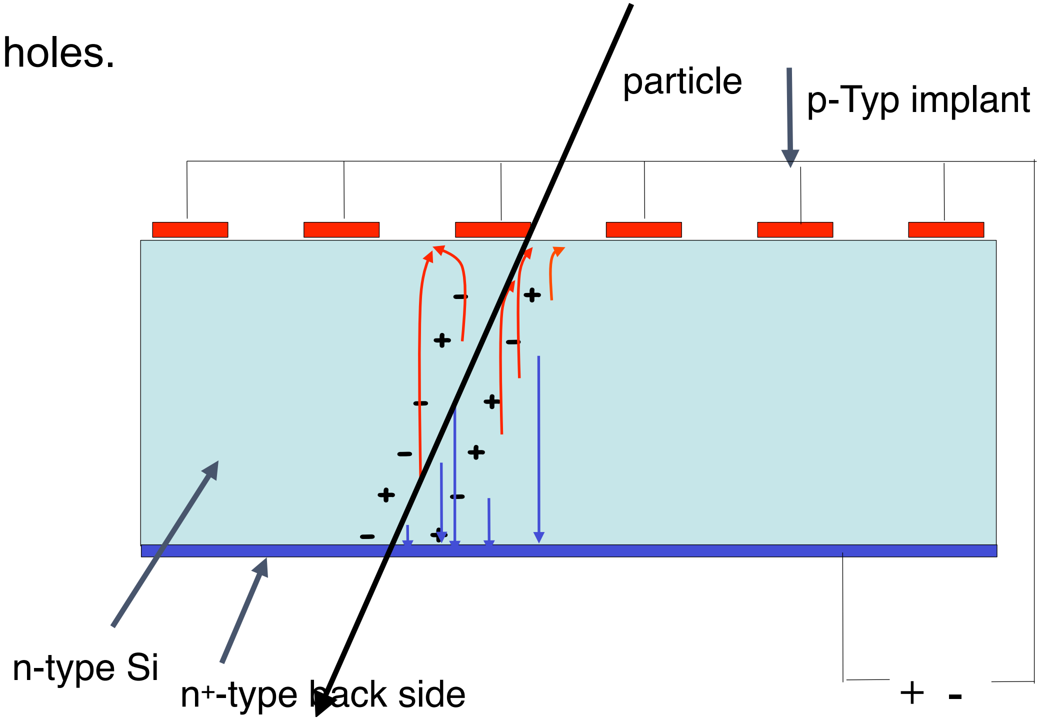


Silicon Detector

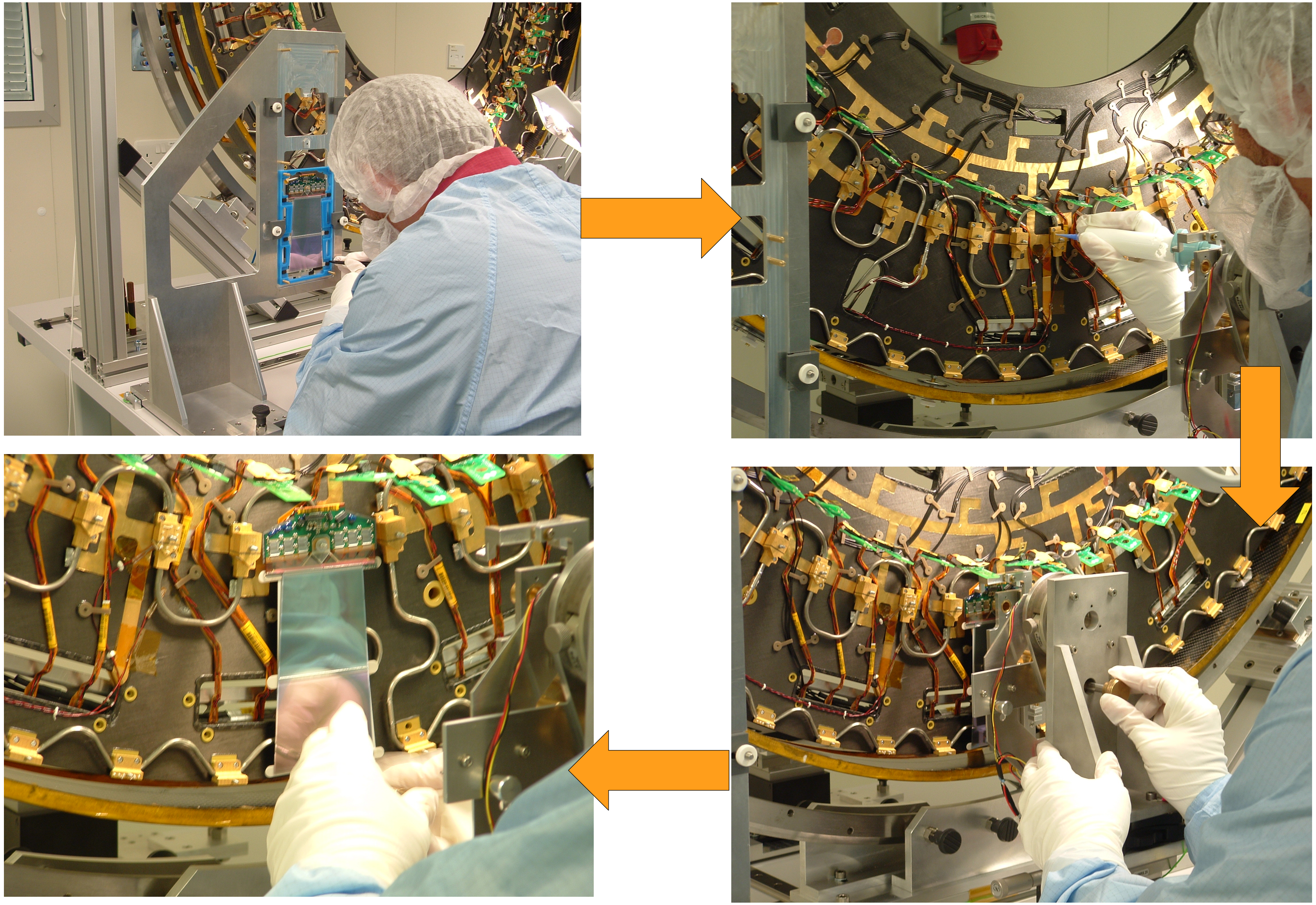
- Segmented p-n diode with applied bias voltage
- Particle creates charges.
- Free carriers diffuse across junction, electrons neutralising the holes.
- Charges drift to contacts
- Signal is read out.

ATLAS Strip Module

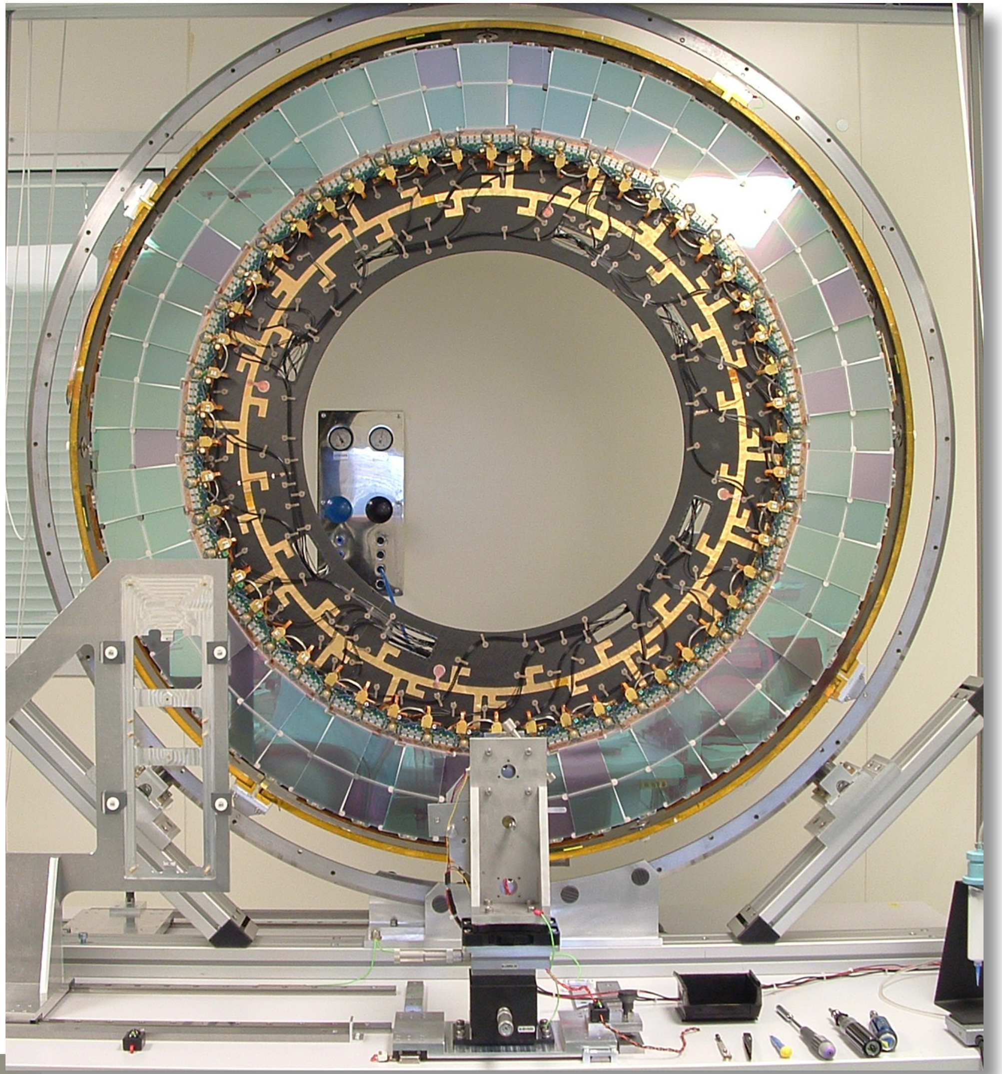


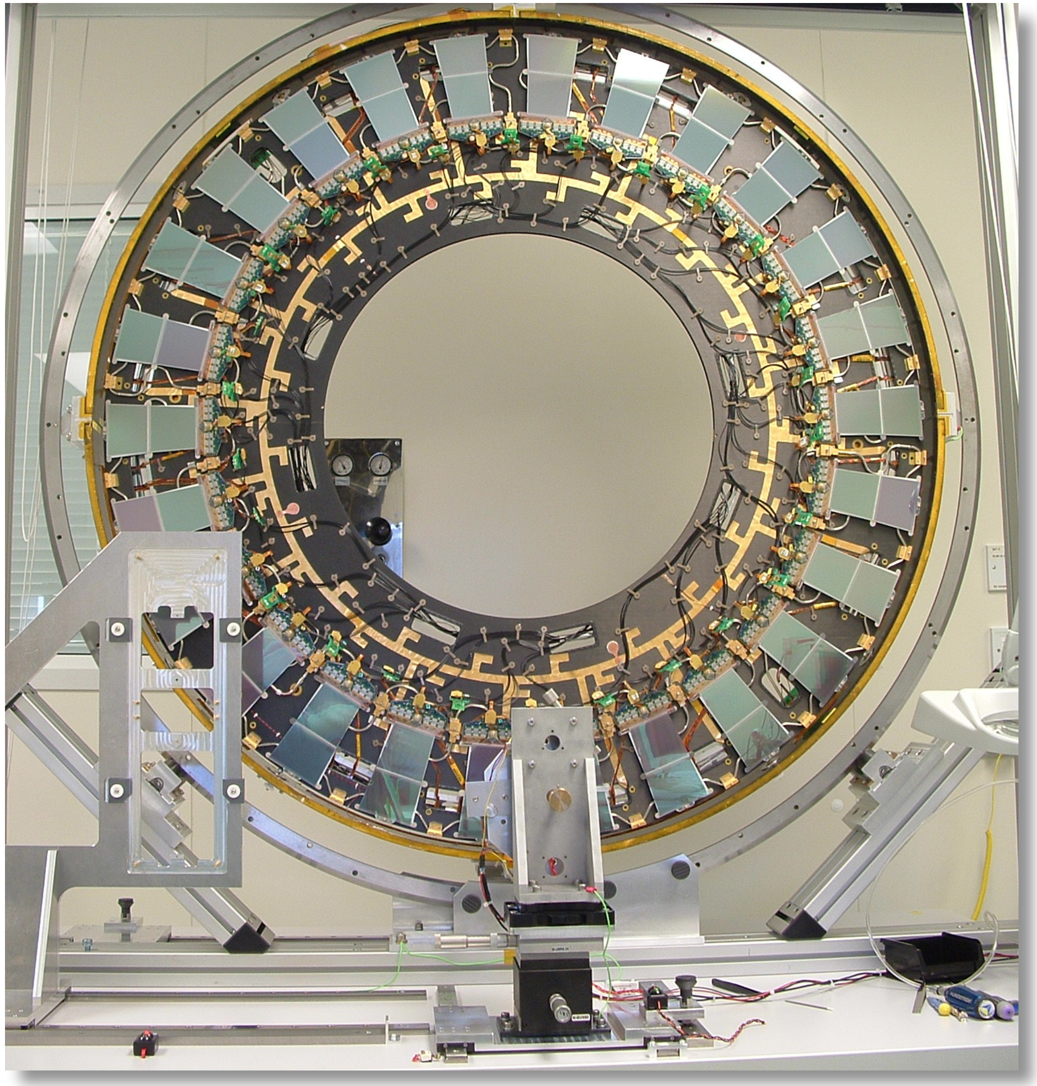


From Module to Detector

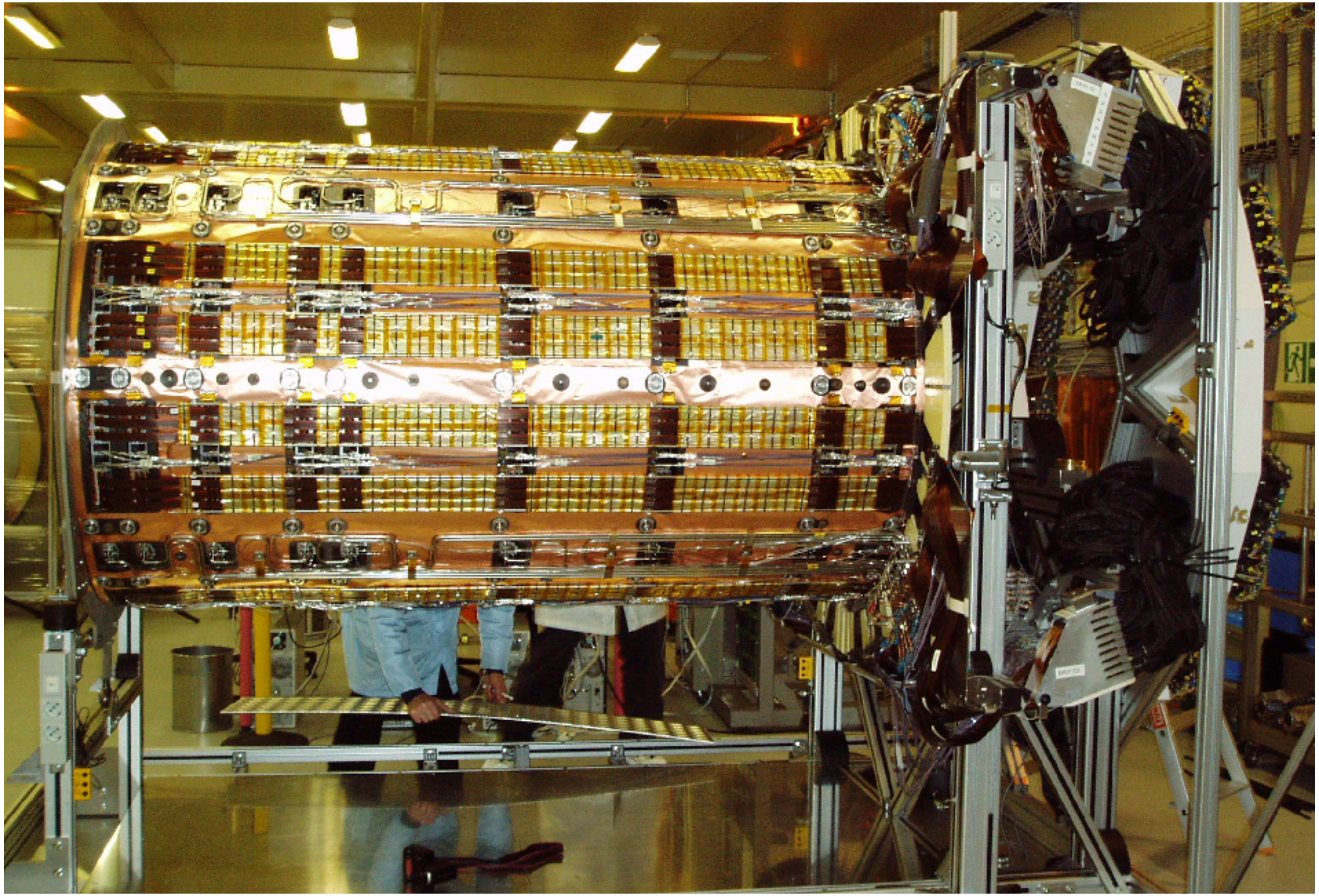


SCT Endcap

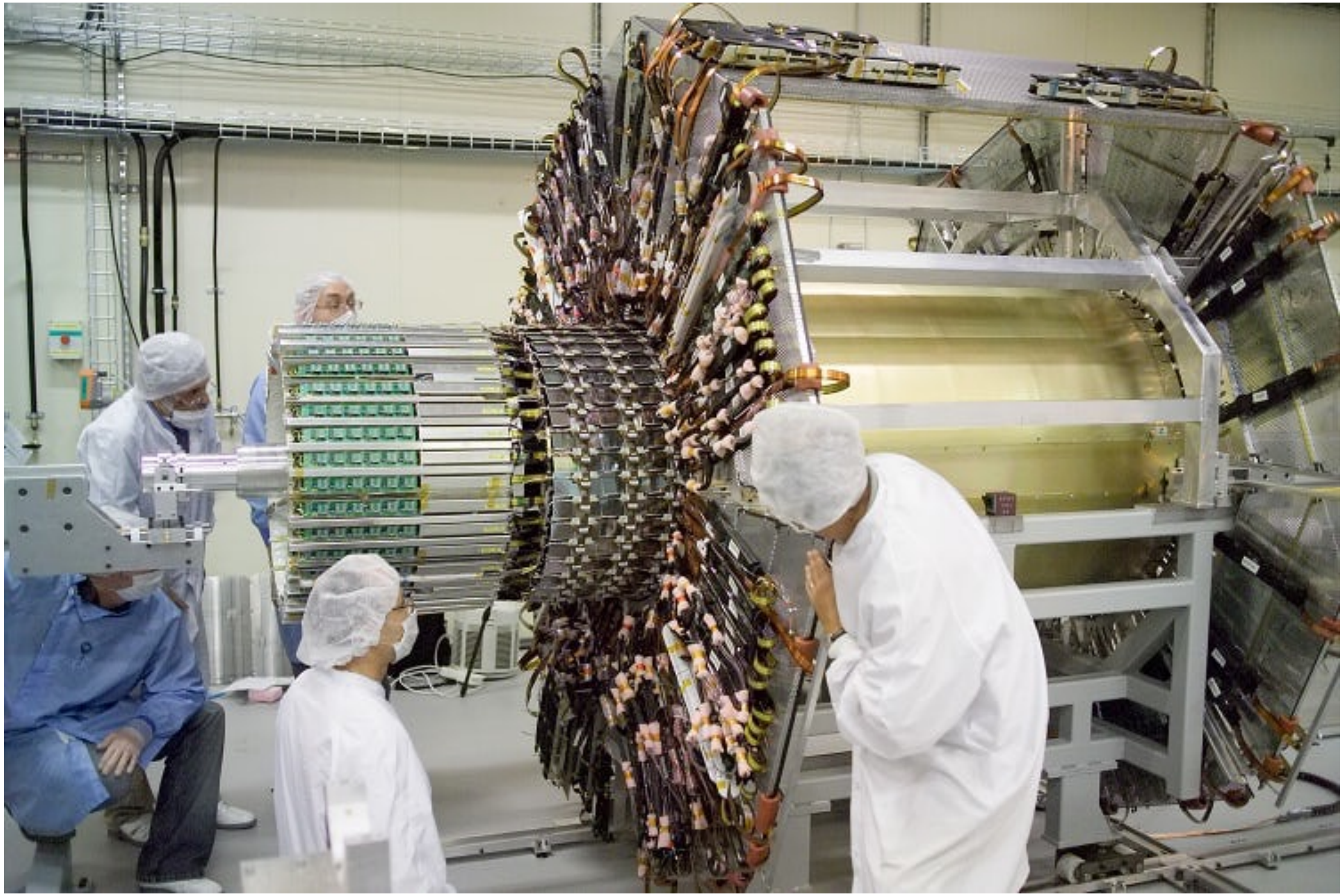




SCT Barrel

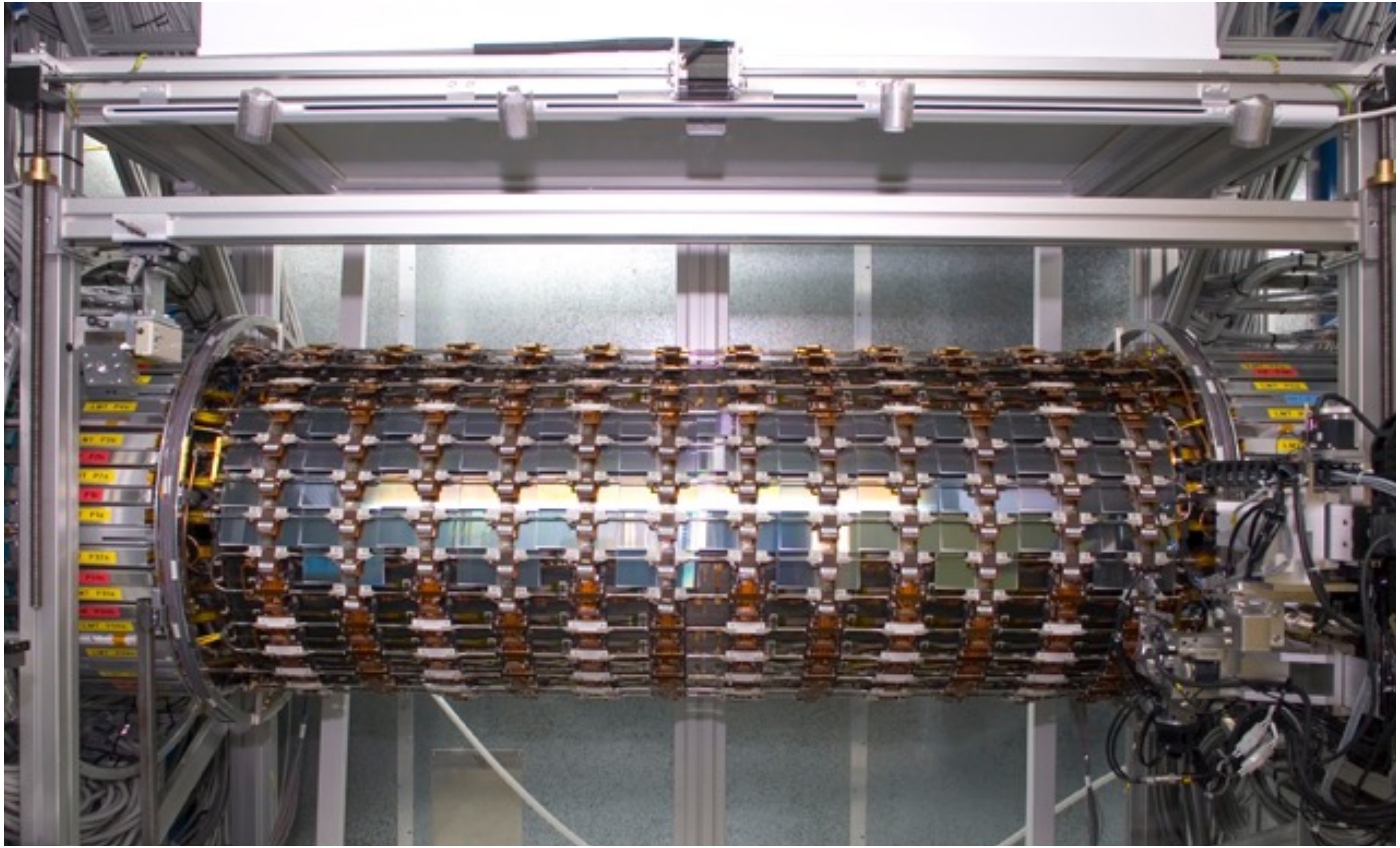


Silicon Tracker (SCT)

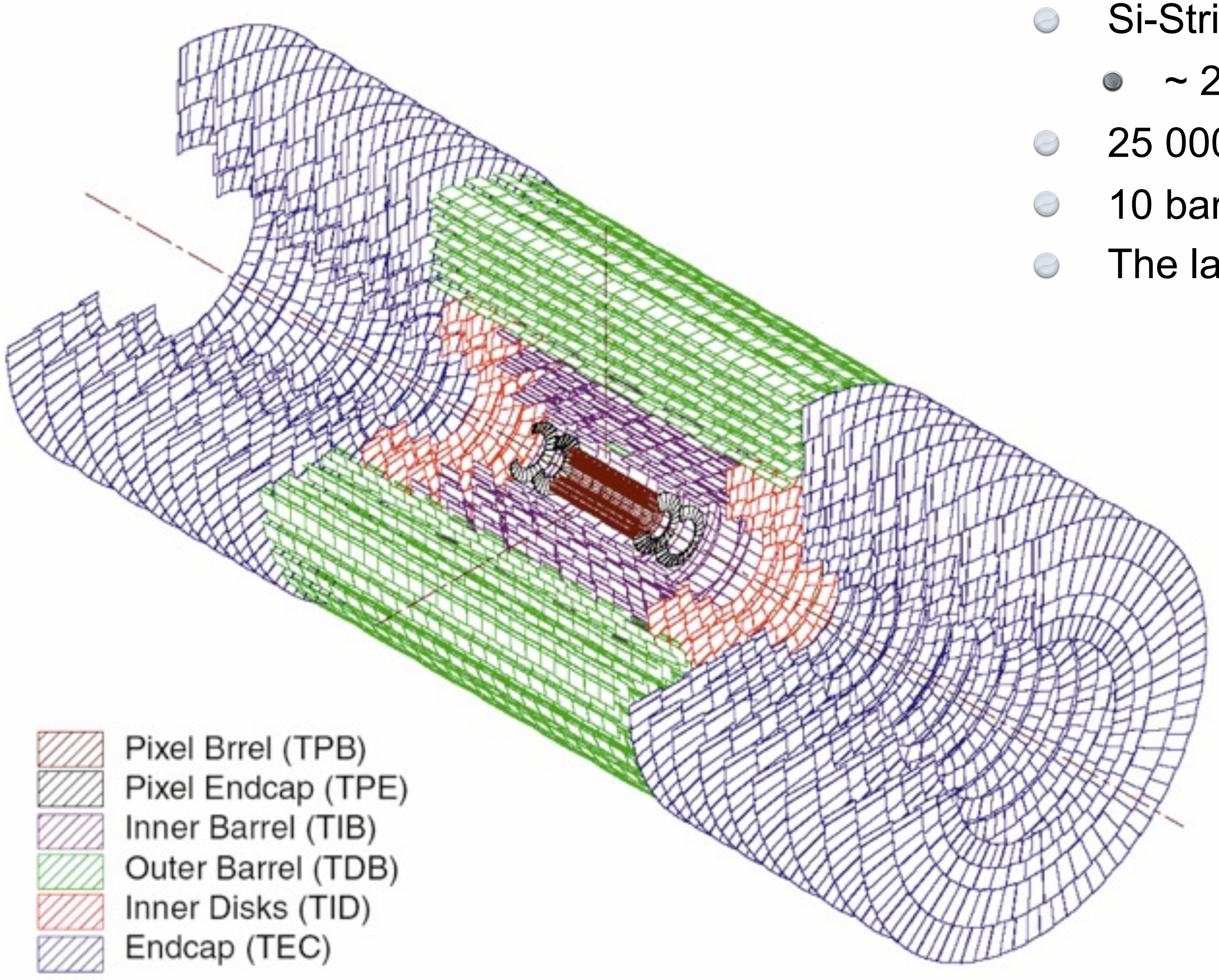


Insertion of the 3rd cylinder (out of the four) into the barrel SCT

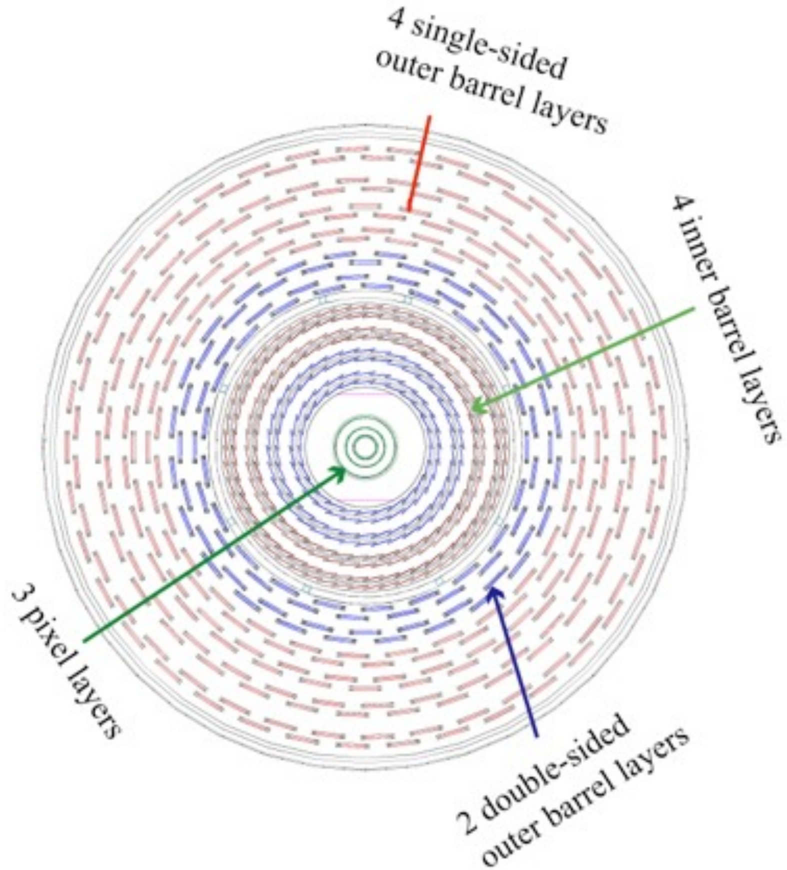
SCT Barrel



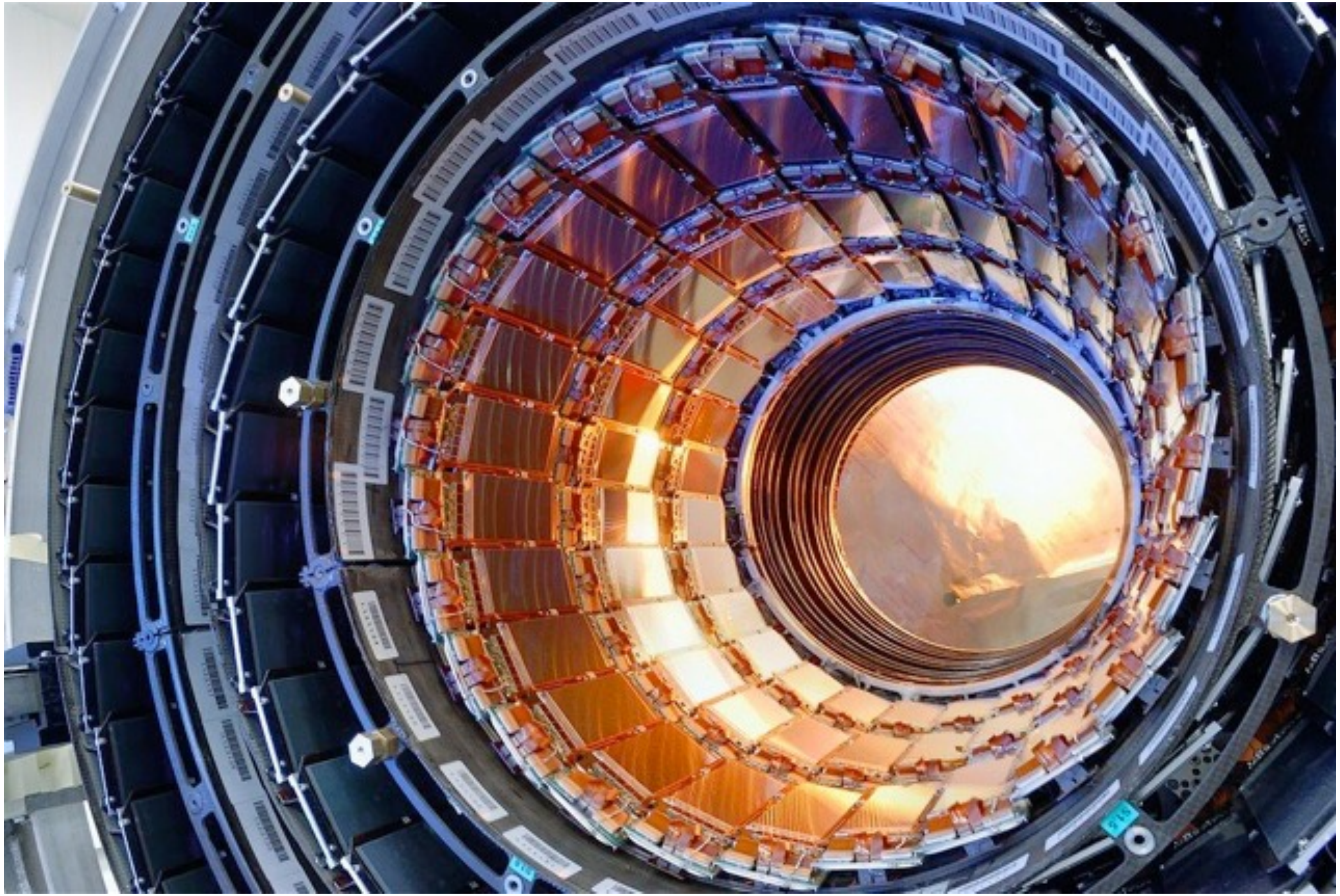
CMS Si-Tracker



- Si-Strip-Detector:
  - ~ 205 m^2 Silicon
- 25 000 Sensors, 9.6 M channels
- 10 barrel layers, 2x 9 discs
- The largest ever built silicon tracker



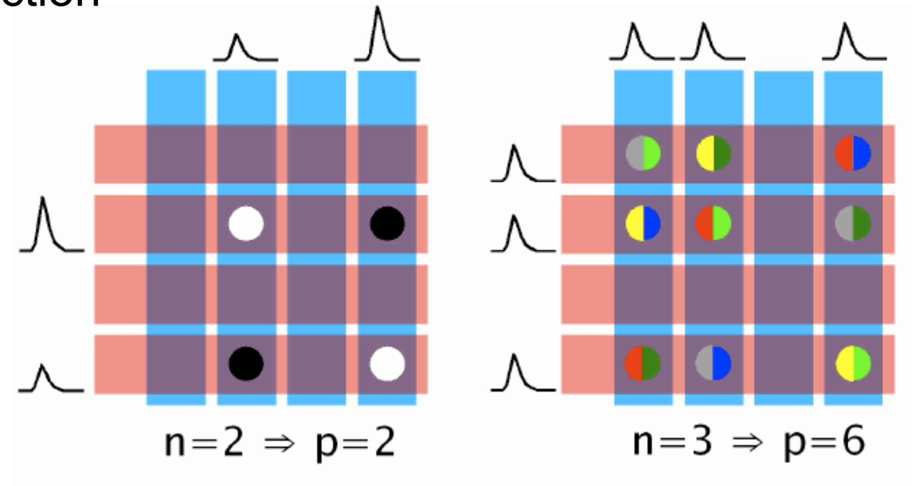
CMS Tracker - Beauty Shot

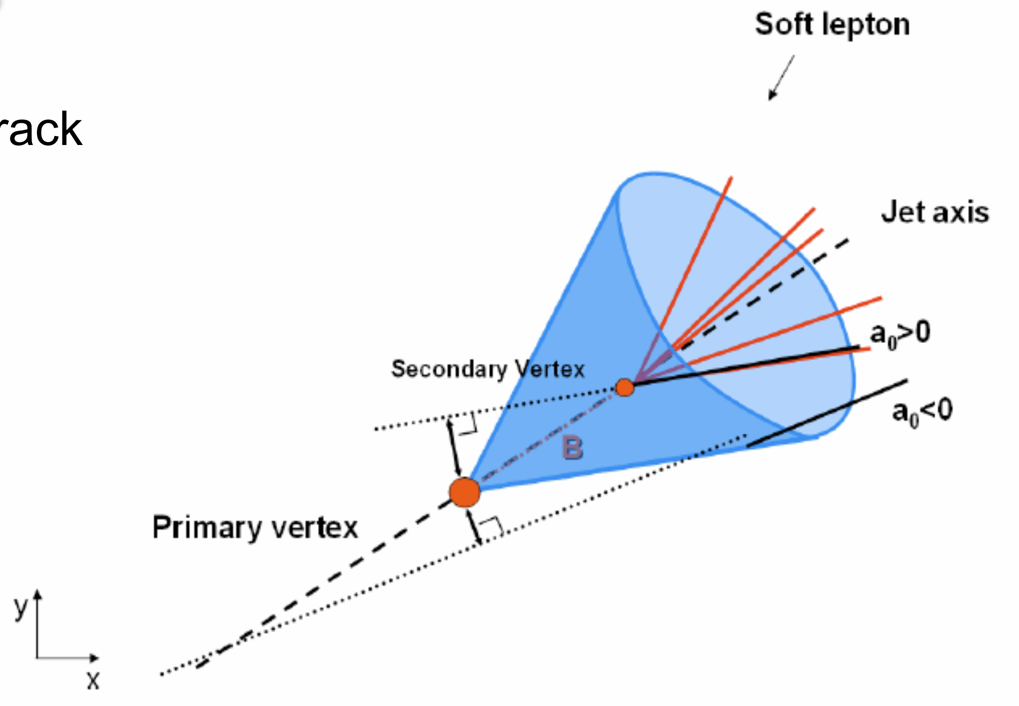


Pic: CERN

Limits of Strip Detectors

- In case of high hit density 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

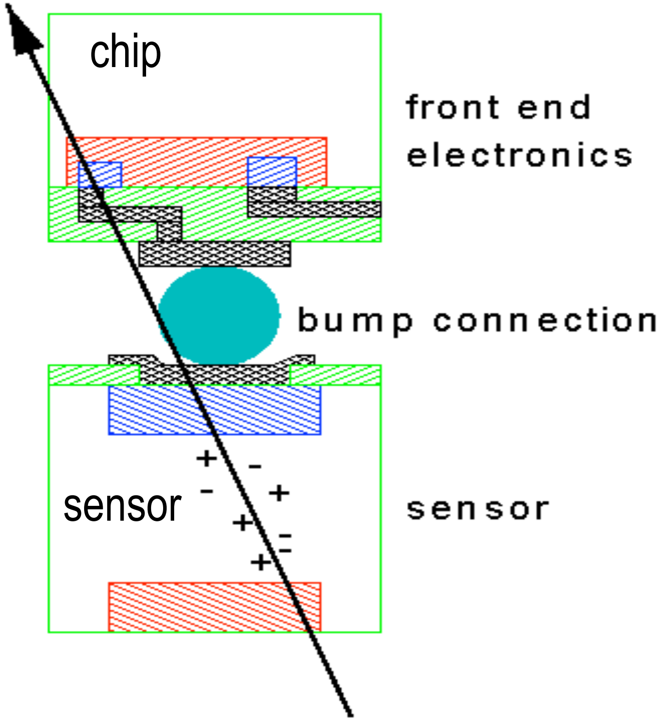
First pixels (CCDs) in NA11/NA32: ~1983

Hybrid Pixels – "classical" Choice HEP

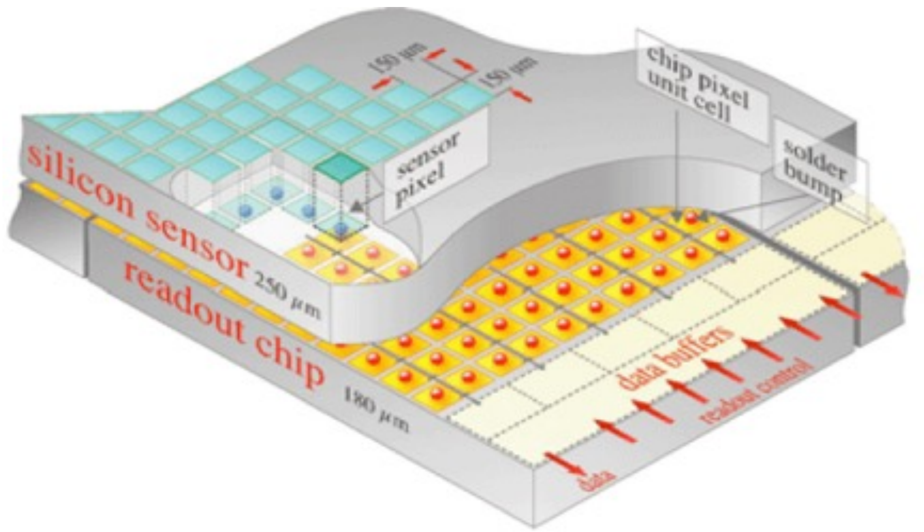
- The read-out chip is mounted directly on top of the pixels (bump-bonding)
- Each pixel has its own read-out amplifier
- Can choose proper process for sensor and read-out separately
- Fast read-out and radiation-tolerant

… but:

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

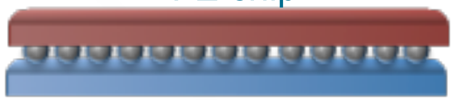


Hybrid Pixel (CMS)



- CMS Pixels: ~65 M channels 150 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@RHIC
- ….

SENSORS FOR HYBRID PIXELS



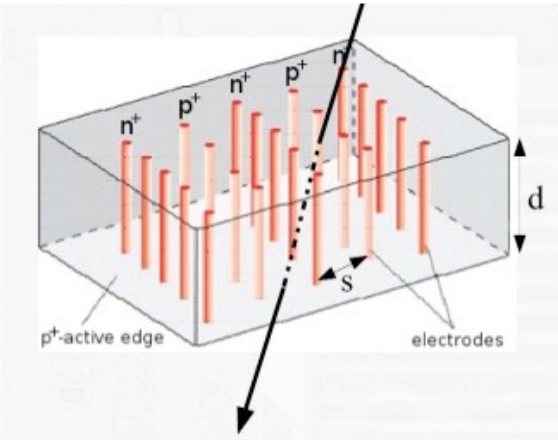
Planar Sensor

- current design is an n-in-n planar sensor
- silicon diode
- different designs under study (n-in-n; n-in-p ....)
- radiation hardness proven up to 2.4 . 10^{16} p/cm^2
- problem: HV might need to exceed 1000V

Very strong R&D efforts to develop sensors for future LHC applications!

3D Silicon

- Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Low charge sharing



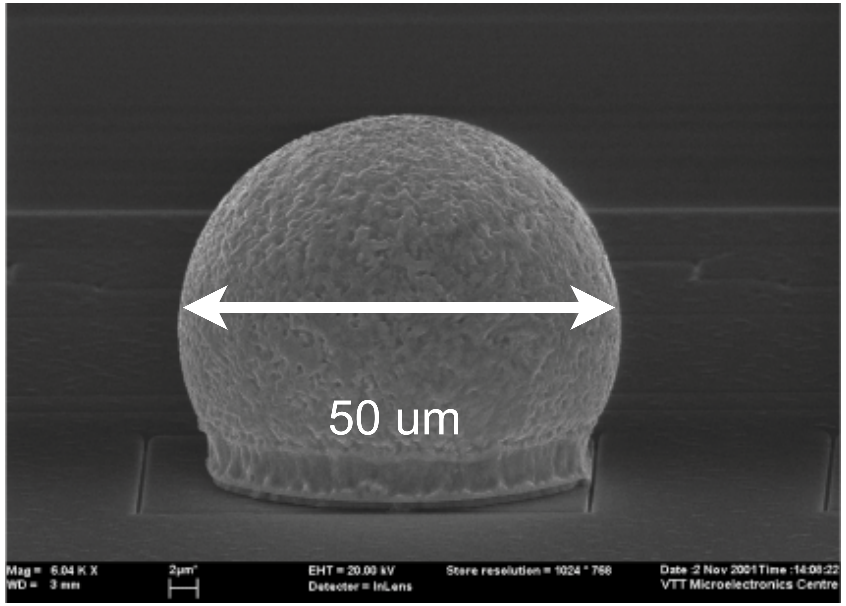
CVD (Diamond)

- Poly crystalline and single crystal
- Low leakage current, low noise, low capacitance
- Radiation hard material
- Operation at room temperature possible
- Drawback: 50% signal compared to silicon for same X_0, but better S/N ratio (no dark current)

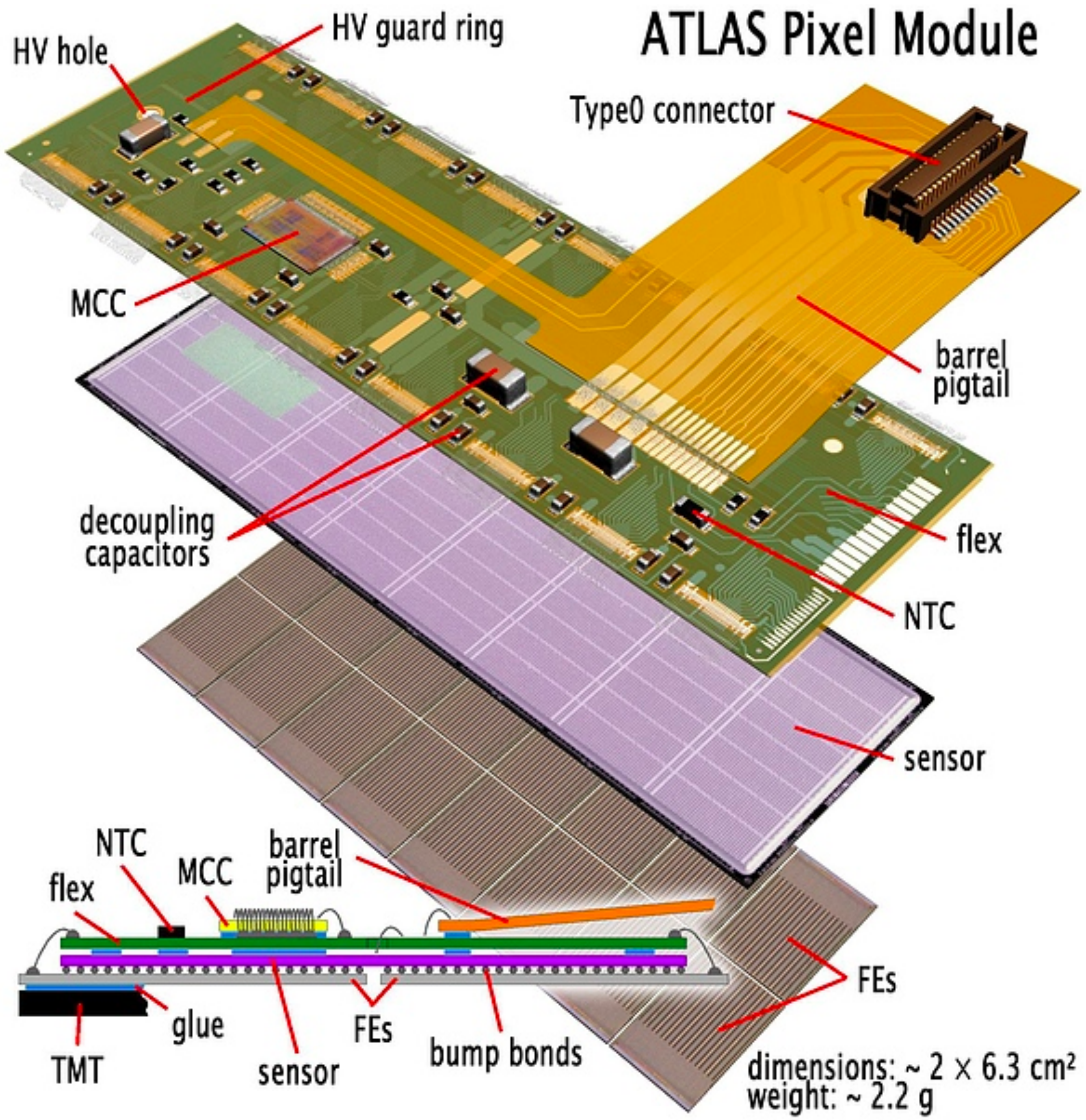
ATLAS-Pixels

A pixel module contains:

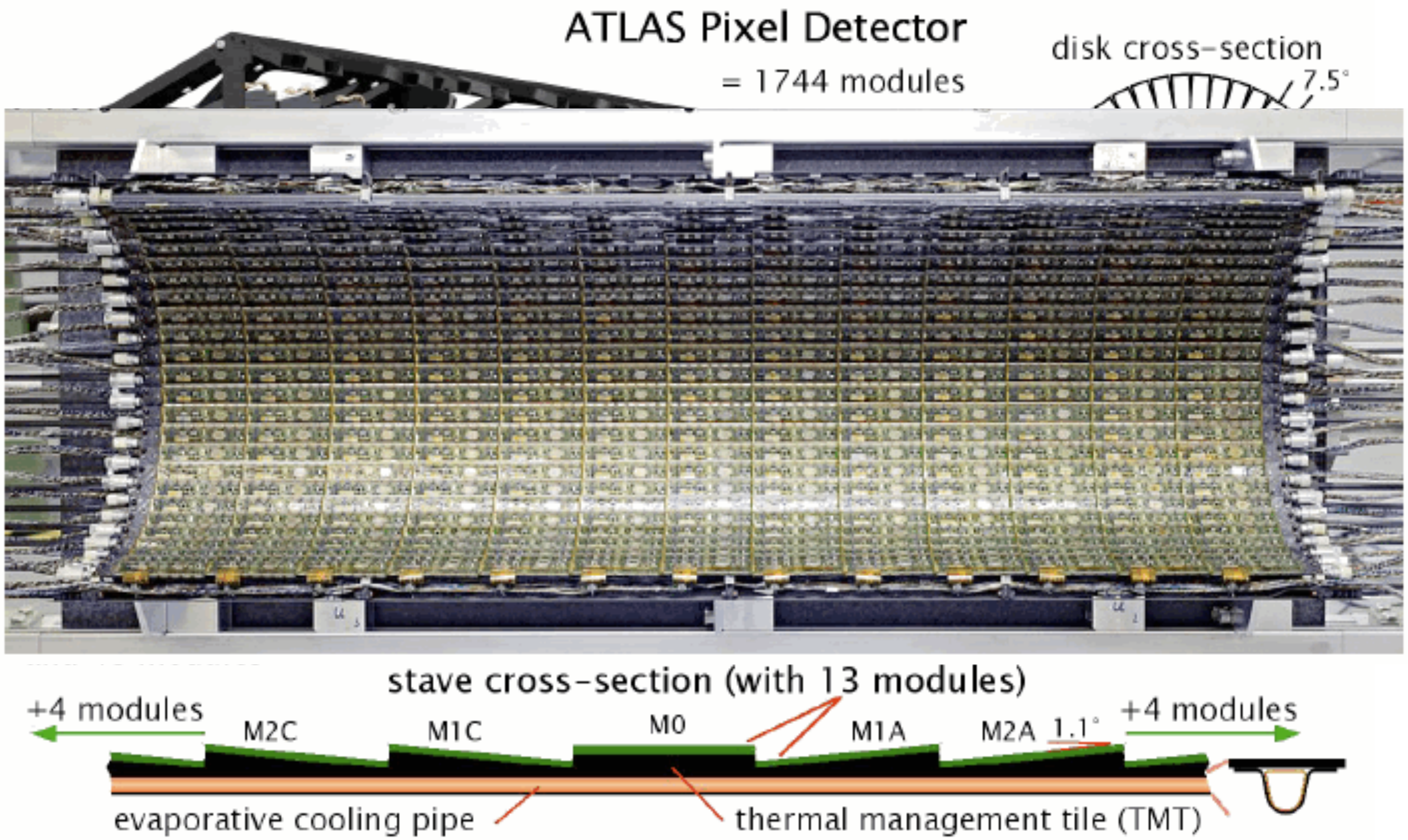
1 sensor (2x6cm)
  ~40000 pixels (50x500 mm)
16 front end (FE) chips
  2x8 array
  bump bonded to sensor
Flex-hybrid
1 module control chip (MCC)
There are ~1700 modules



Picture: VTT



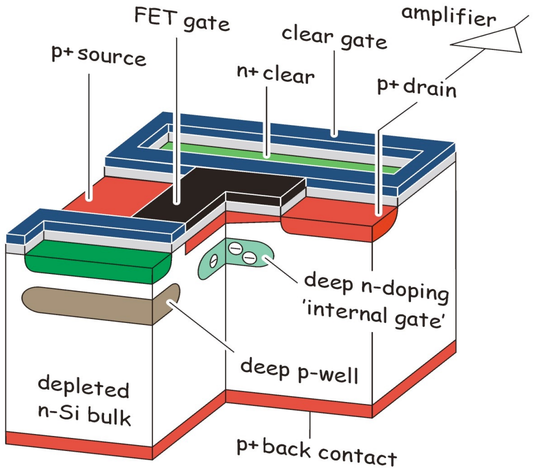
ATLAS-Pixels



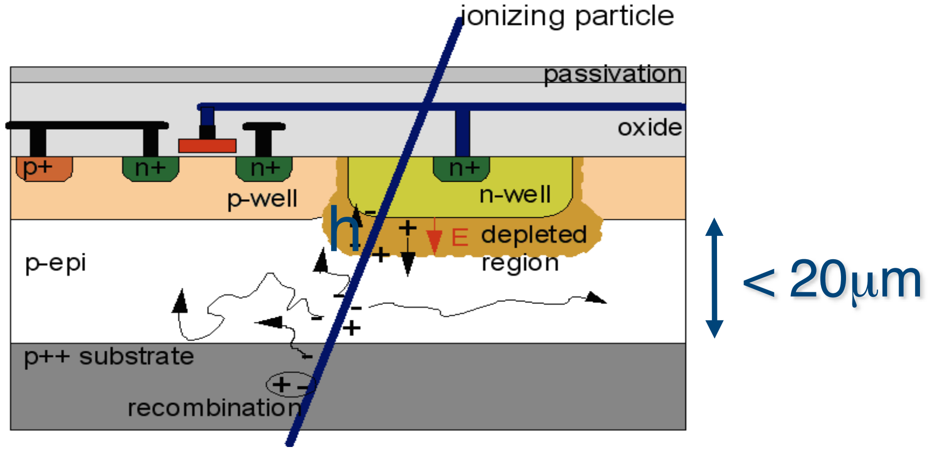
Monolithic Pixel Sensors

- Some HEP applications (Linear Collider etc.) require extremely good spatial resolution (factor 2-5 better than at LHC) and very low material in the tracker
- Hybrid pixel sensors are too thick for such applications
- Investigating technologies with sensor and readout electronics in one layers -> monolithic
- Four different technologies:
  - CCD, DEPFET, CMOS, and 3D
  - different variants of each technology approach under investigation

- Some of them where chosen as baseline technology for real experiments
  - DEPFET for Belle II @KEK (Japan)
  - Mimosa MAPS for Star @ RHIC (USA)



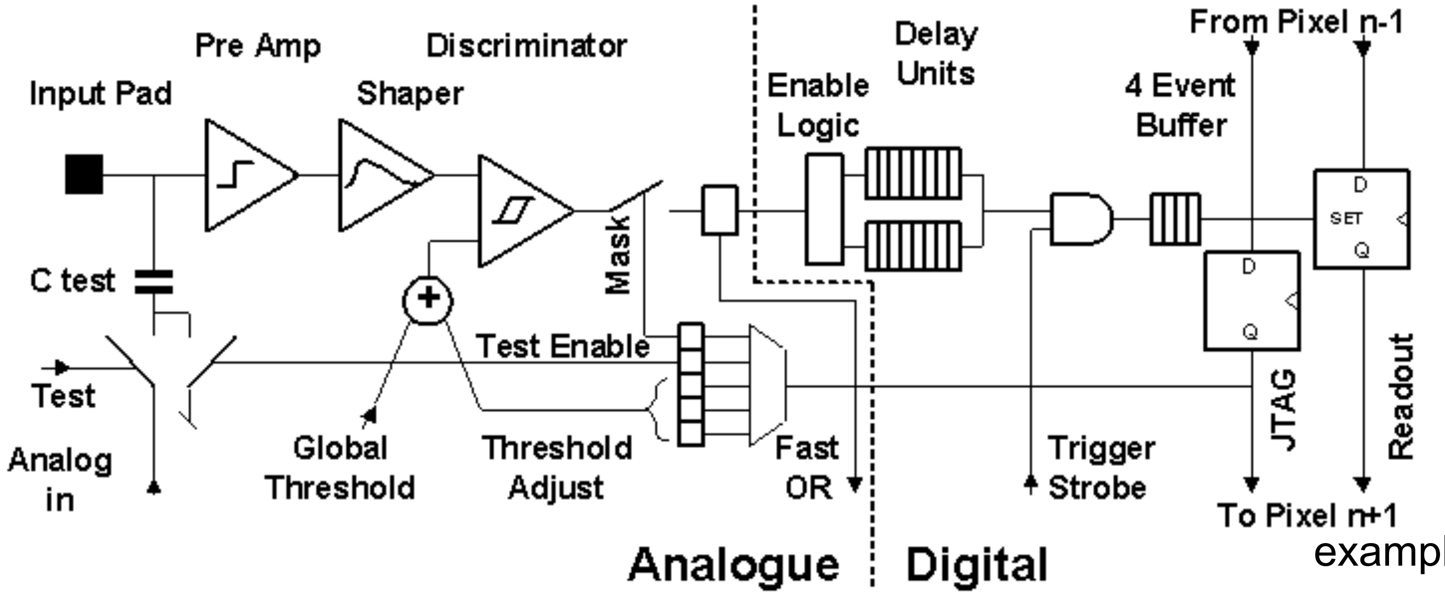
DEPFET



Mimosa MAPS

Overview of readout electronics

- Most front-ends follow a similar architecture

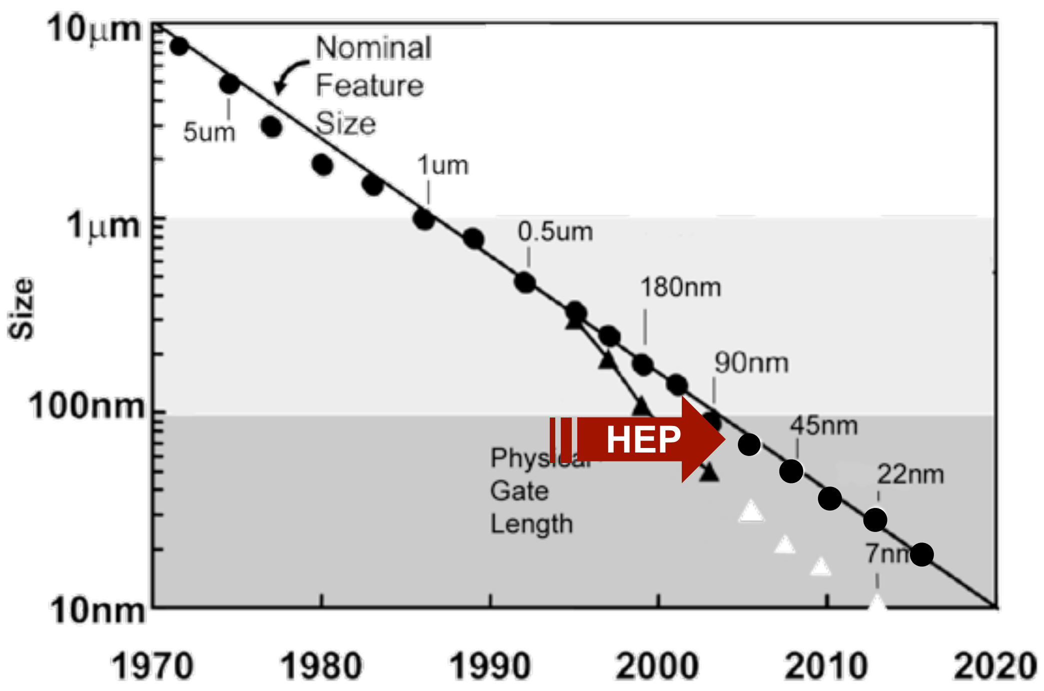


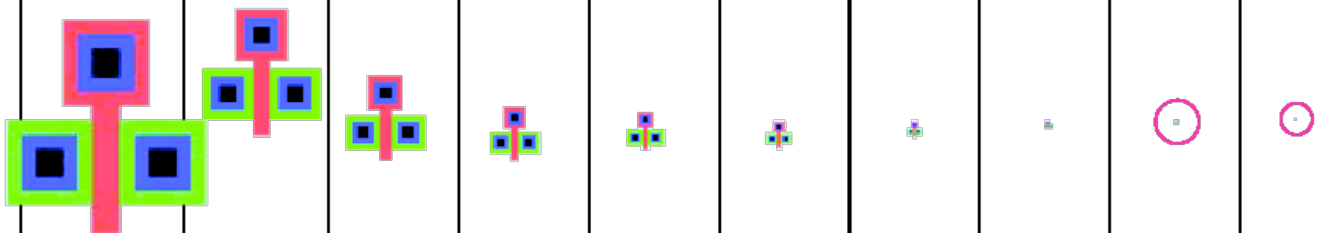
example: ALICE Pixel detector

- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discriminators, TDCs)
- Several thousands to millions of channels
- Also here very detailed R&D ongoing to adapt to future challenges in HEP
  - more radiation hard, higher occupancy, smaller strip/pixel pitch etc.
  - adapting new CMOS technologies for HEP applications

Industry Scaling Roadmap

- New generation every ~2 years with $\alpha = \sqrt{2}$
  - from 1970 (8 µm) to 2013 (22 nm) (industrial application)
- End of the road ? Power dissipation could set limits
- HEP nowadays at 65nm and 130nm
- Problem: by the time a technology is ready for HEP -> “old” in industry standards
- Super expensive ….



Feature Size [nm]	2000	1200	800	500	350	250	130	65	35	20
Minimum NMOS										

Coffee Break