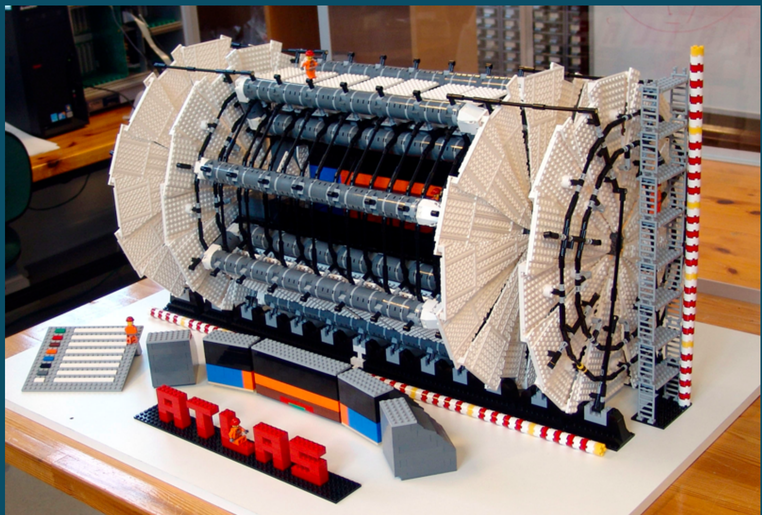
Detectors for High Energy Physics

Ingrid-Maria Gregor, DESY



DESY Summer Student Program 2013
Hamburg
July 29th/31st 2013

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

Monday

V. **Tracking Detectors**
- Gas detectors
- Semiconductor trackers

Wednesday

VI. **Examples from the real life**

V. Tracking Detectors

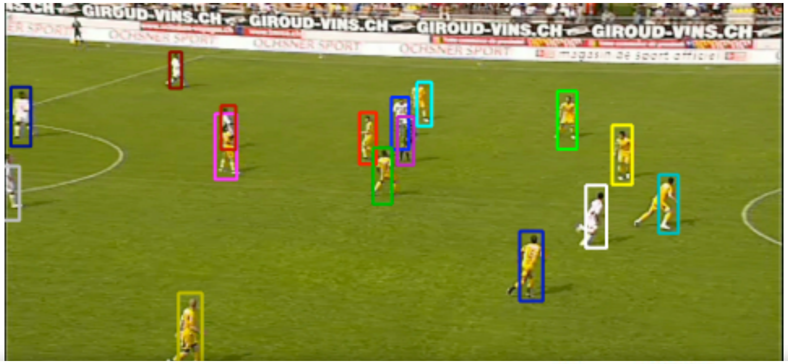
Tracking

- “tracking” in google image search:

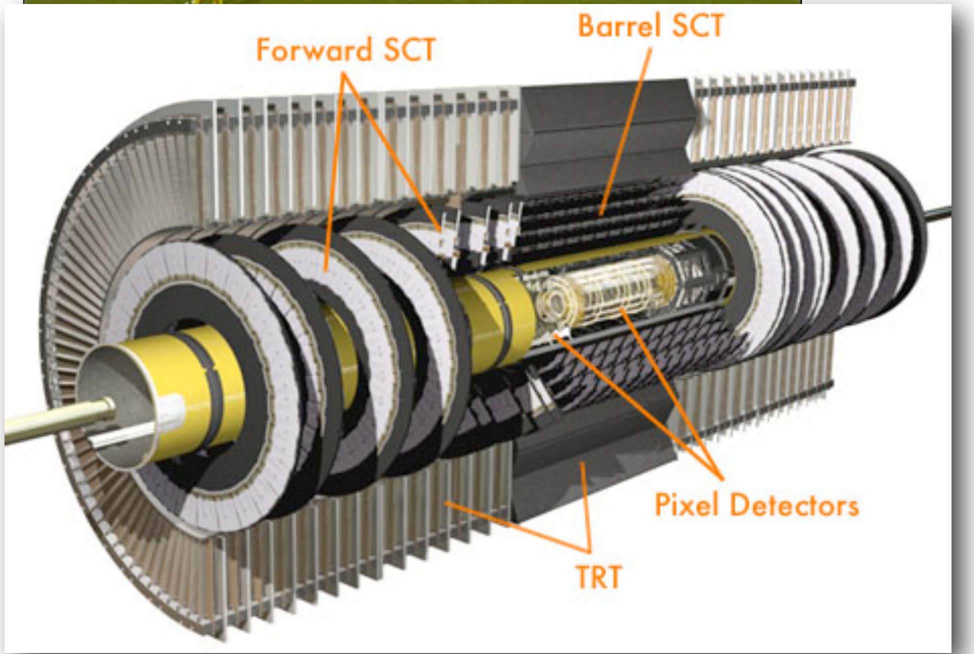
Tracking Detector

- “tracking detector” in google image search

GPS Tracking Detector



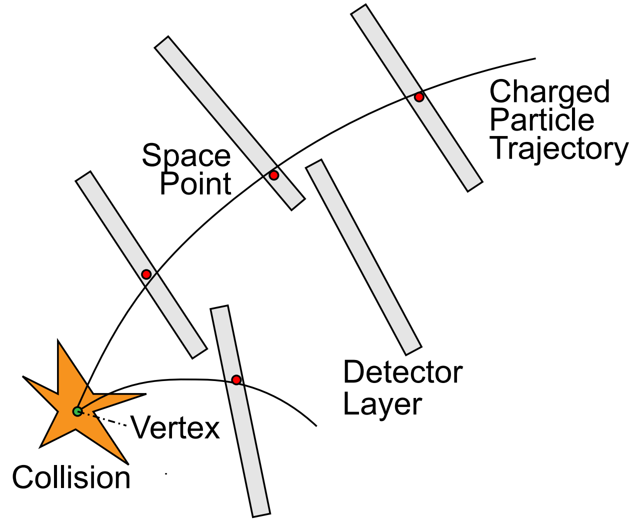
But the 1st image on list is:



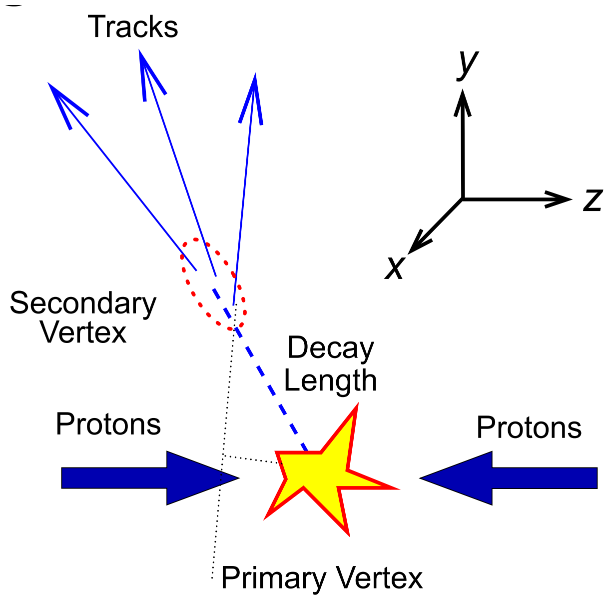
Pic: ATLAS Collaboration

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)



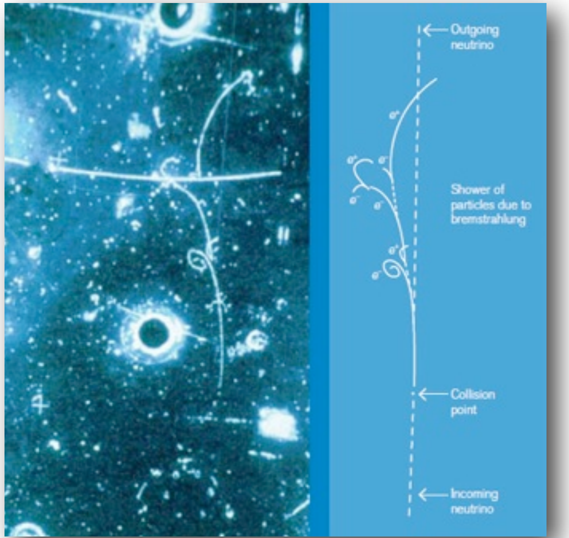
- Charged particles ionize matter along their path.
  - Tracking is based upon detecting ionization trails.
  - An “image” of the charged particles in the event



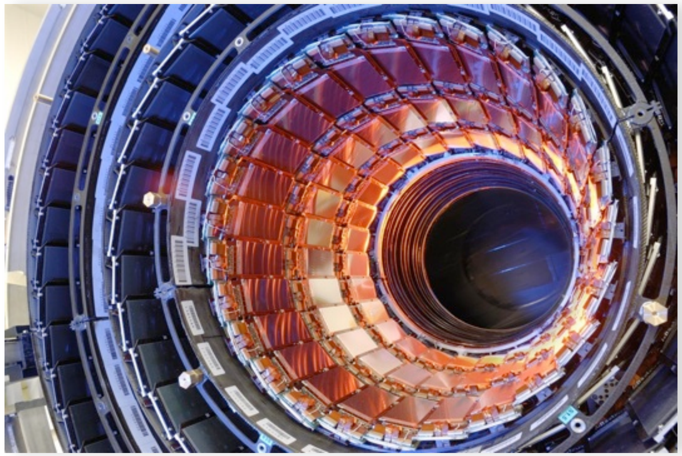
Pictures: U. Husemann

Tracking Detectors - Technolgies

- **"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)



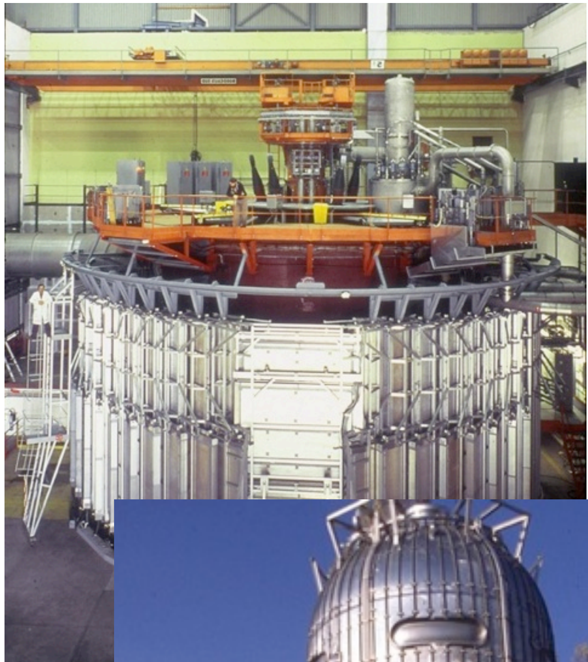
Discovery of neutral currents
Gargamelle, 1972

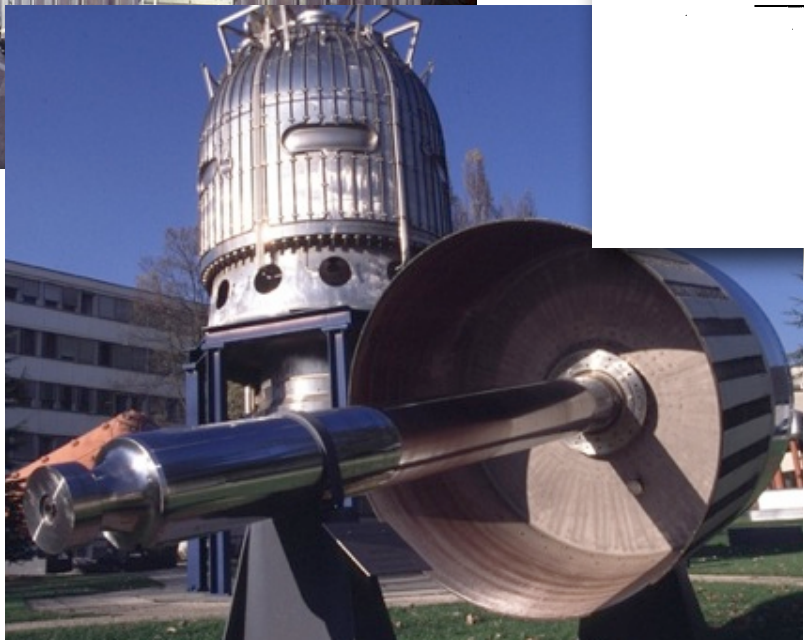


CMS Inner barrel Si Tracker:
Single-Sided Si-Strip

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….”

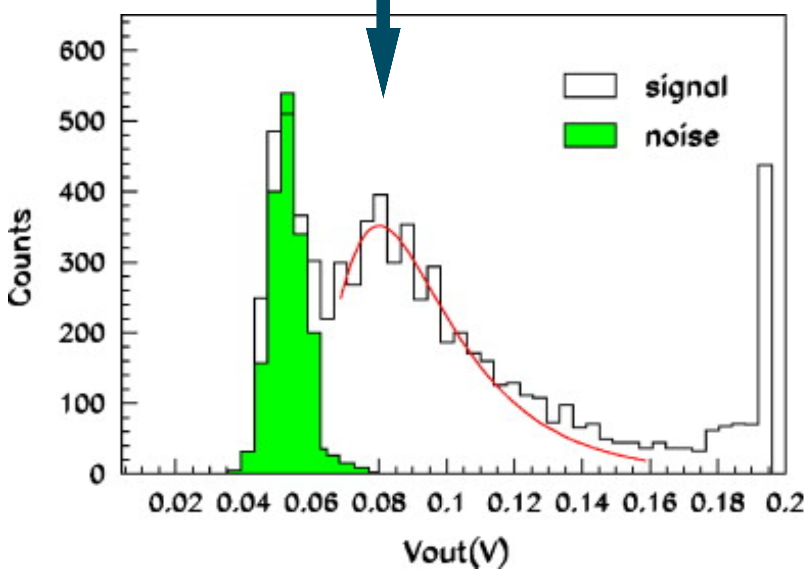
Tracker: Important Parameter

- **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 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

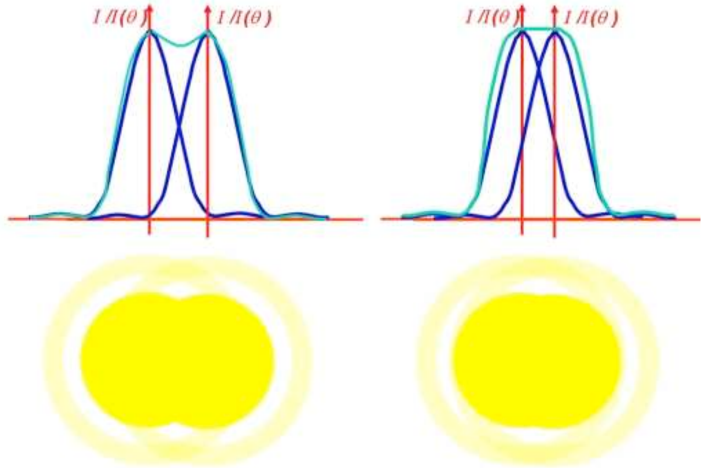
$$\mathrm{ENC} = \sqrt{\mathrm{ENC}_C^2 + \mathrm{ENC}_I^2 + \mathrm{ENC}_{R_p}^2 + \mathrm{ENC}_{R_s}^2}$$

example for silicon detector

most probable peak!



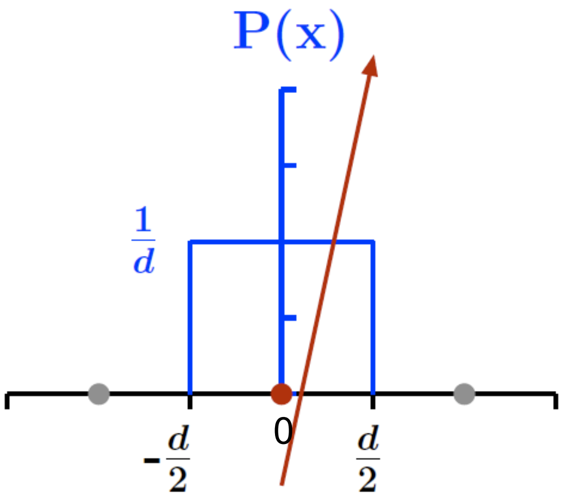
Tracker: Important Parameter



- 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

  - 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:

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

Tracker: Important Parameter

- Calculating the resolution orthogonal to the strip:

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

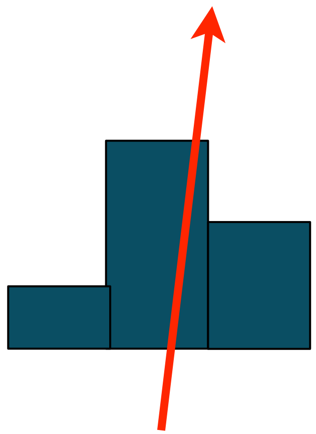
- Resulting in a general term (valid for tracking detectors with a pitch d):

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

very important !

- 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 additional information of adjacent channels

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



Tracking: Determination of the 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

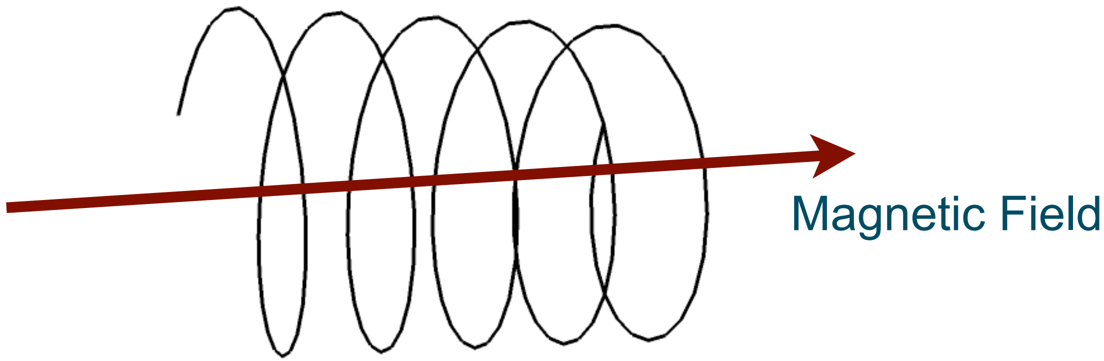
Radius of the circular path is proportional to the transversal momentum

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

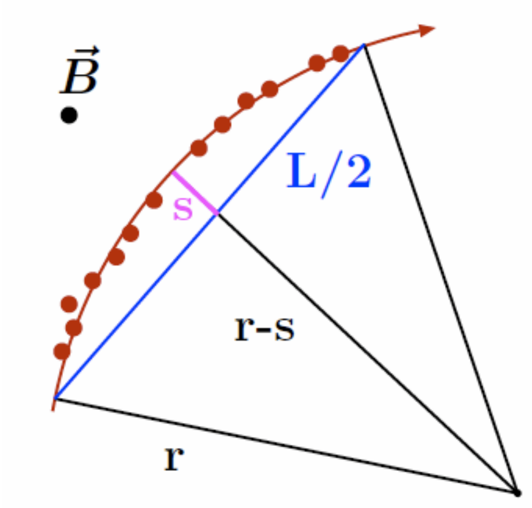
when converting in HEP units and assuming that all particles have the |electron charge|

- parallel to the field is no deflection:

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



Determination of the Momentum in Magnetic Field II



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

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

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

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:

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

NIM, 24, P381, 1963

➠ 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

Impuls resolution: Spatial resolution and multiple scattering

- More components are influencing the momentum resolution $\sigma(p_T)/p_T$ of a tracking system:
  - Inaccuracy of the tracking detector: $\sigma(p_T) \propto p_T$
  - Influence of the particle due to MS: $\sigma(x)_{MS} \propto \frac{1}{p}$
  - The angular resolution of the detector

Multiple scattering angle: $\theta \propto \frac{1}{p}$

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

Position resolution — Multiple scattering — Angular resolution

- p_T resolution improves as 1/B and depends on p as $1/L^2$ or $1/L^{-1/2}$
- For low momentum ($\beta \rightarrow 0$), MS will dominate the momentum resolution.
- Improving the spatial resolution (σ_y) only improves momentum resolution if the first term is dominate.

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

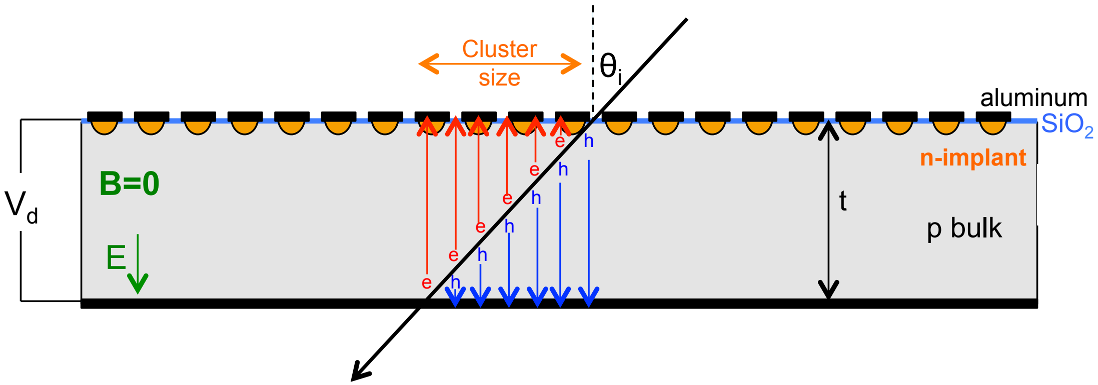
$$\epsilon_{\text{track}} = (\epsilon_{\text{layer}})^n$$

n = number of layer is tracking system

$$\epsilon_{\text{track}} = (\epsilon_{l1}) \cdot (\epsilon_{l2}) \cdot (\epsilon_{l3}) \cdot \ldots \cdot \epsilon_{l12})$$

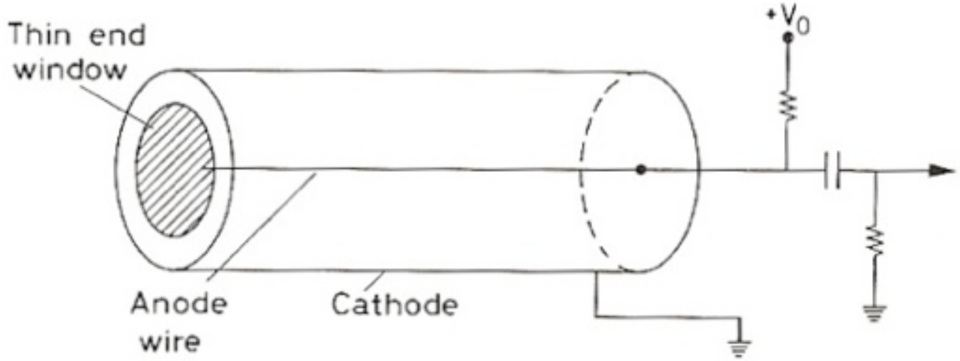
- **Cluster size** : number of hit pixels/strips belonging to one track
  - usually given in unit of strips or pixels
  - depending on angle of incidence

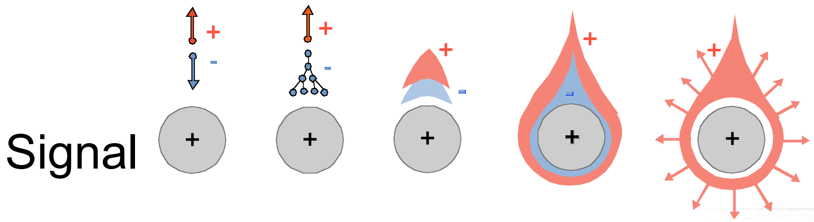
Needs to be measured in test beam ….

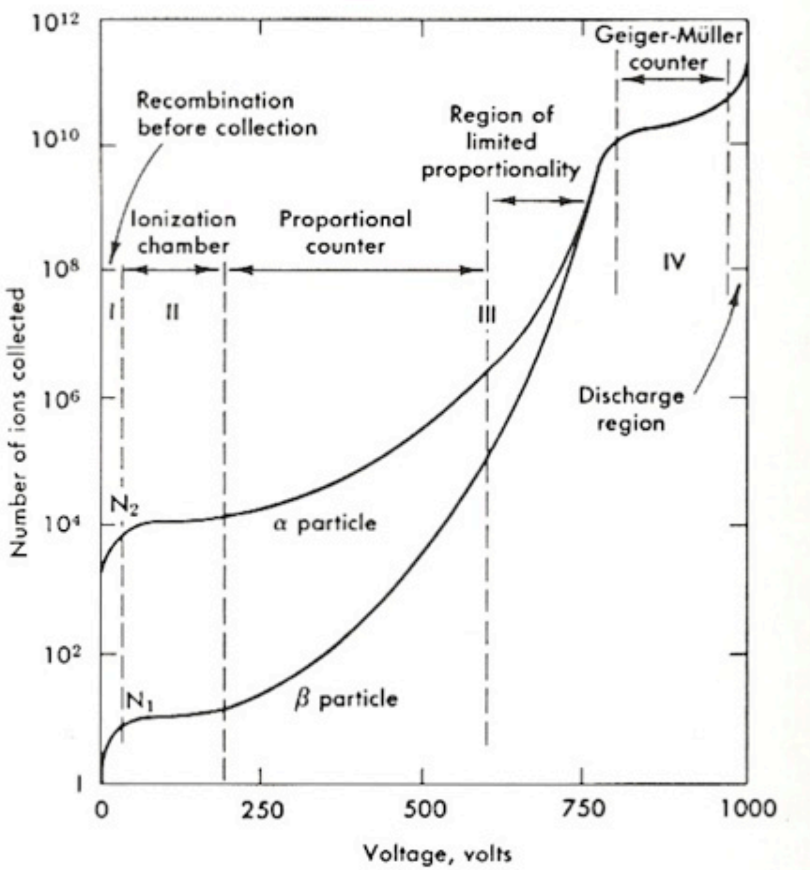


V.a Gas-Detektoren

Another Classic: Ionisation Chamber



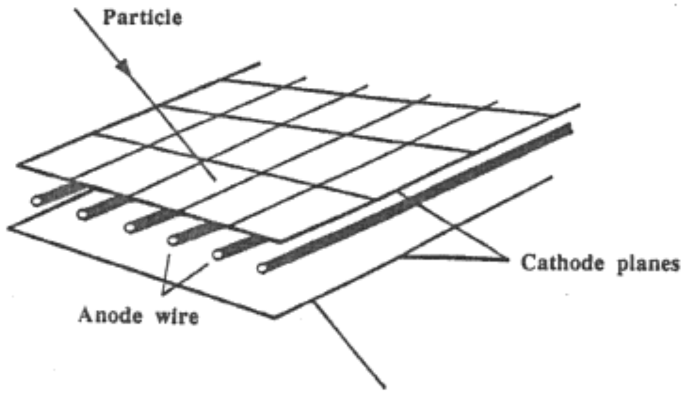


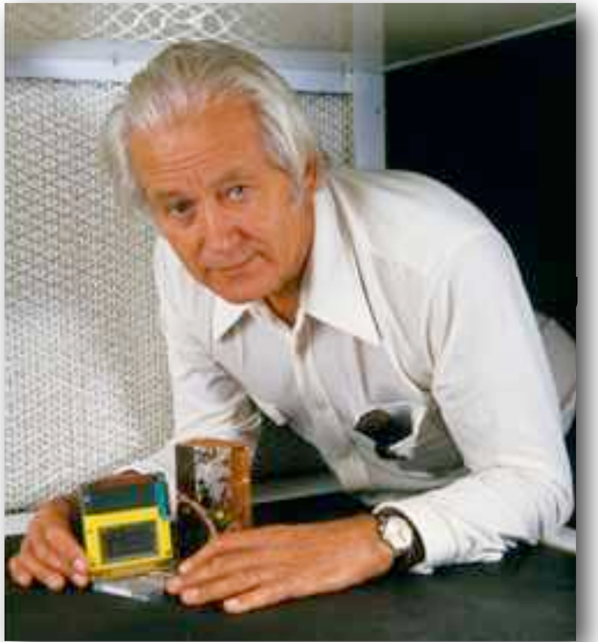


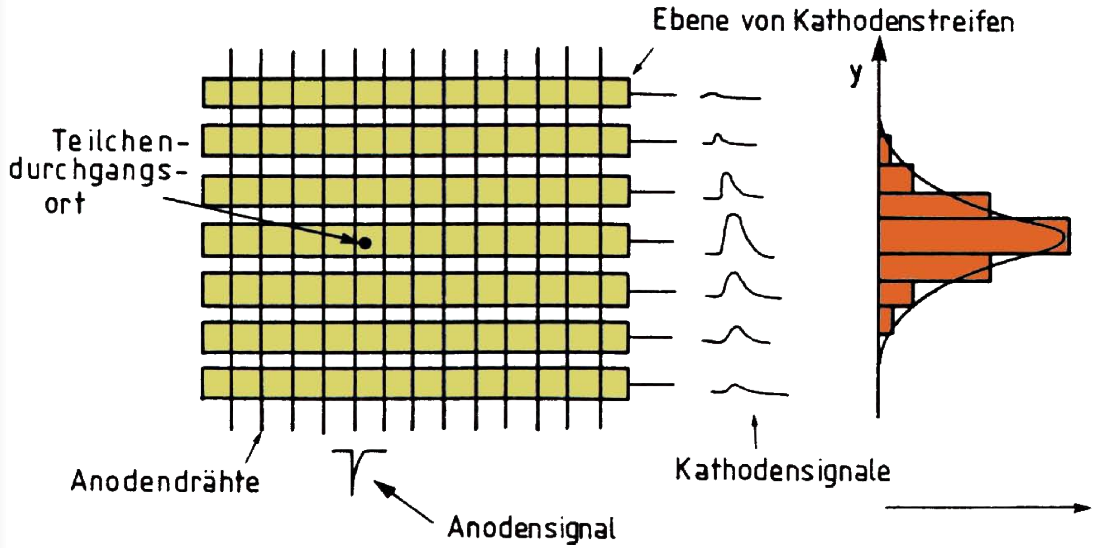
- Passage of particles creates within the gas volume electron-ion pair (ionisation)
- Electrons are accelerated in a strong electrics field -> amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)

Continuation of Ionisation Chambers

- Extreme successful approach to improve the spatial resolution of gas detectors
- Multi wire proportional chamber (MWPC)
- Gas-filled box with a large number of parallel detector wires, each connected to individual amplifiers
- G. Charpak 1968
(Nobel-Preis 1992)







Adding the Time: Drift chamber

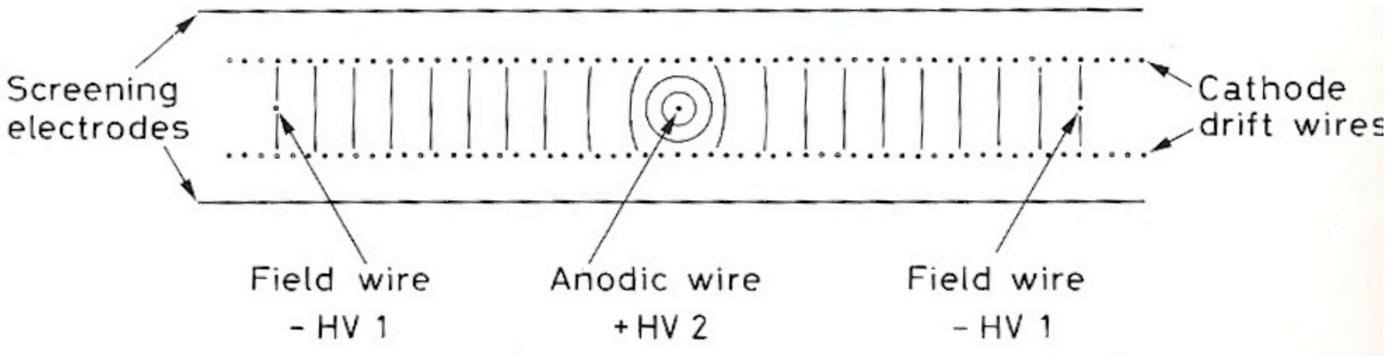
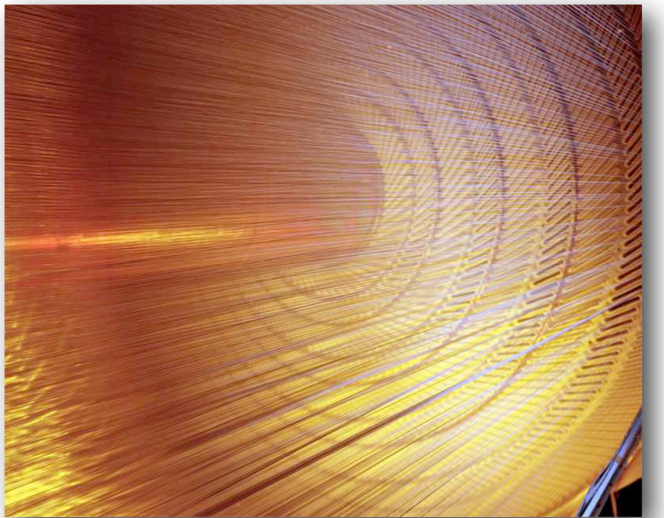


Fig. 6.16. Drift chamber design using interanode field wires (from *Breskin* et al. [6.22])

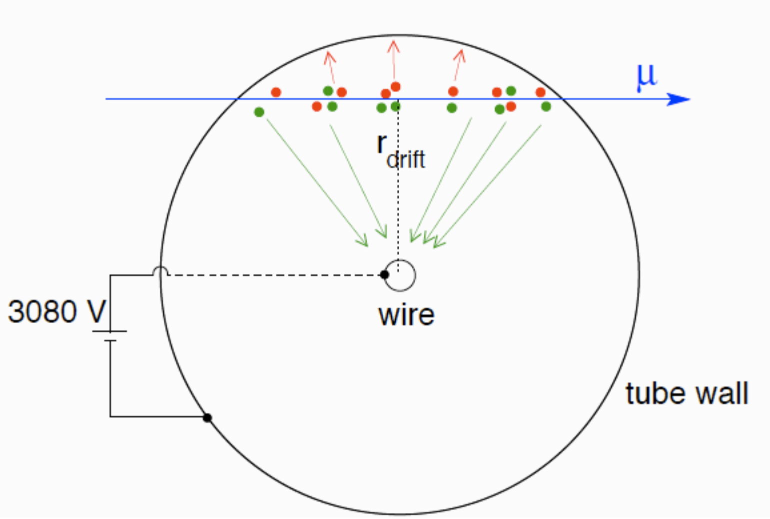
- Electric field is designed in a way that electrons drift with a constant velocity and only amplify very close to the wire
- If time of arrival of a particle is known (trigger), one can derive from the signal arrival time at the anode the position of the track
- Condition: the HV field distribution and therefore the drift velocity within the gas is well known



Wire chamber CDF (@Tevatron)

Commonly used: Drift Tube

- Example: ATLAS Muon-System



Measurement of the drift time: defines the smallest distance of the track to the wire

➪ right/left ambiguity: multiple layers shifted to each other necessary

➪ spacial resolution typically ~100 μm

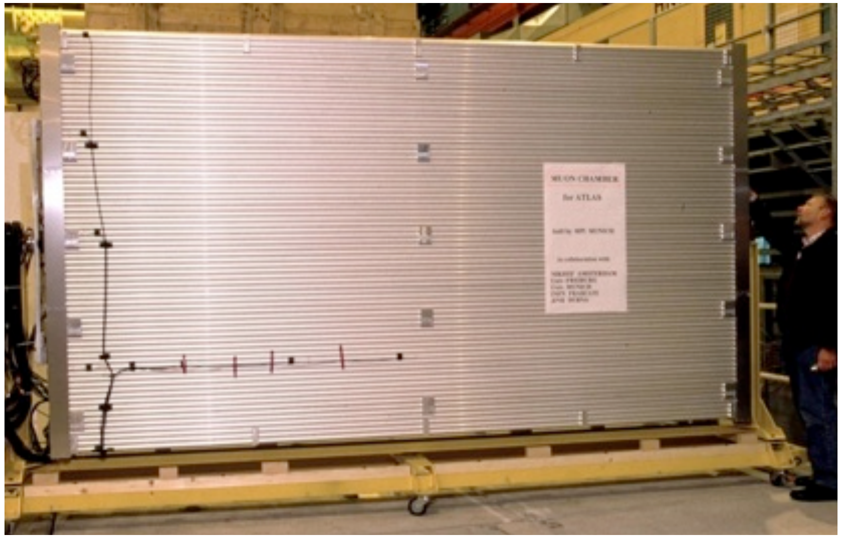
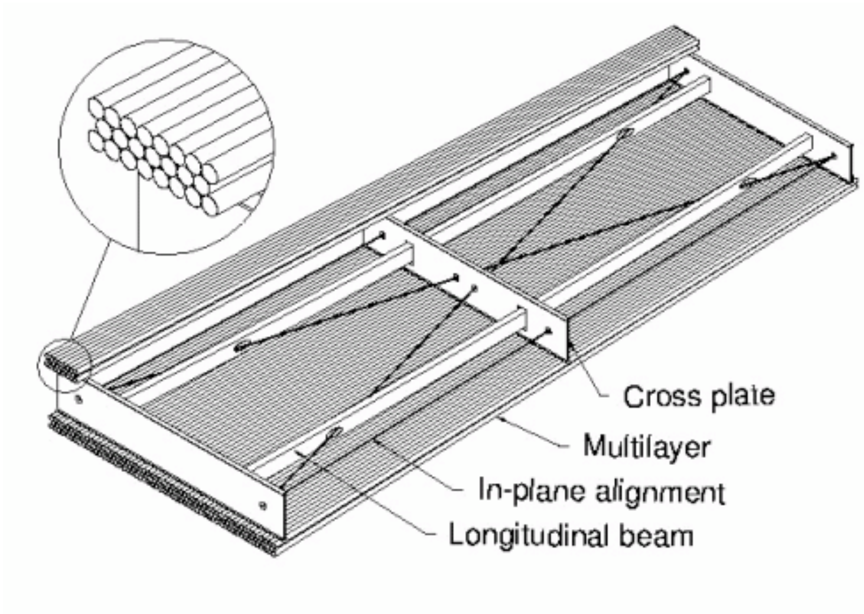
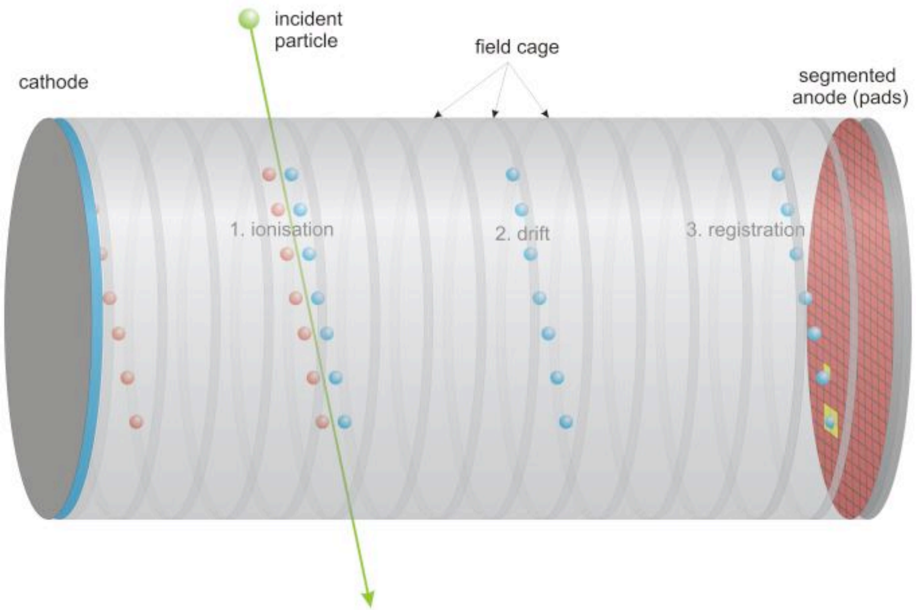


Foto: CERN

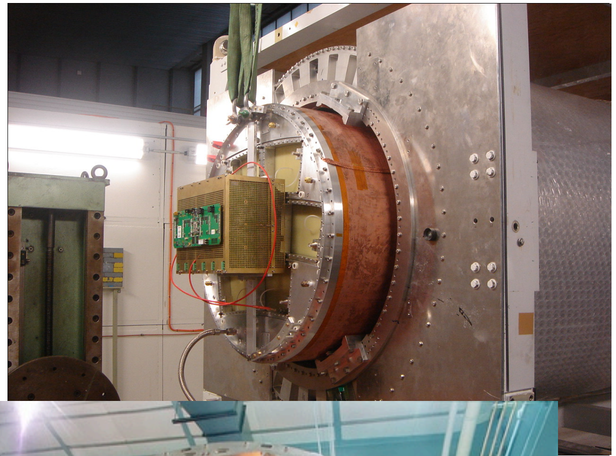


TPC- Time Projection Chamber: 3D

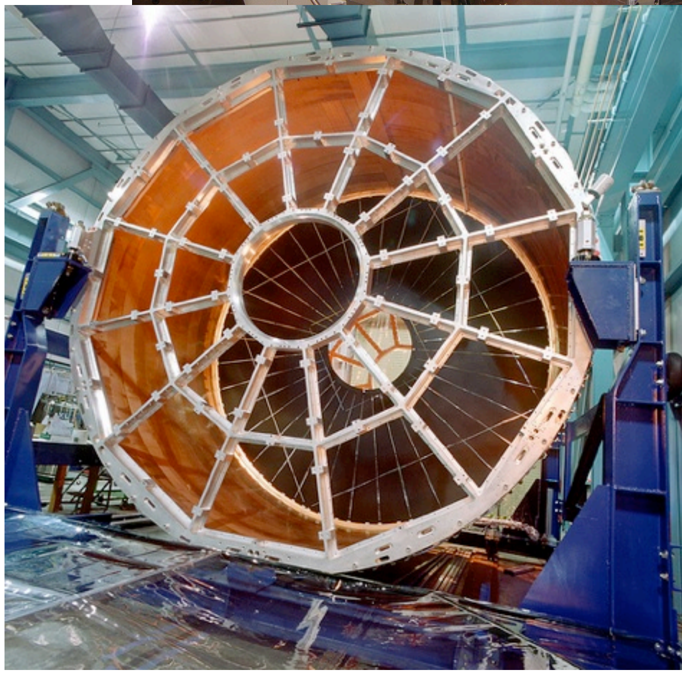
- Combination of the the 2D track information and the time results in a real 3D point



Pic: O. Schäfer



Pic: DESY



Pic: ALICE Collaboration

- Readout of the anode usually with multi wire projection chambers
- Nowadays new developments under way.

New Developments

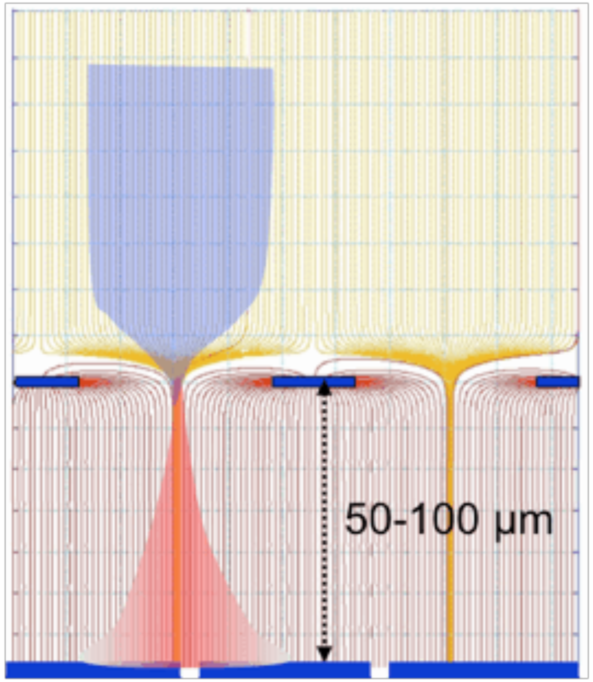
- Largely improved spacial resolution and higher particle rates:

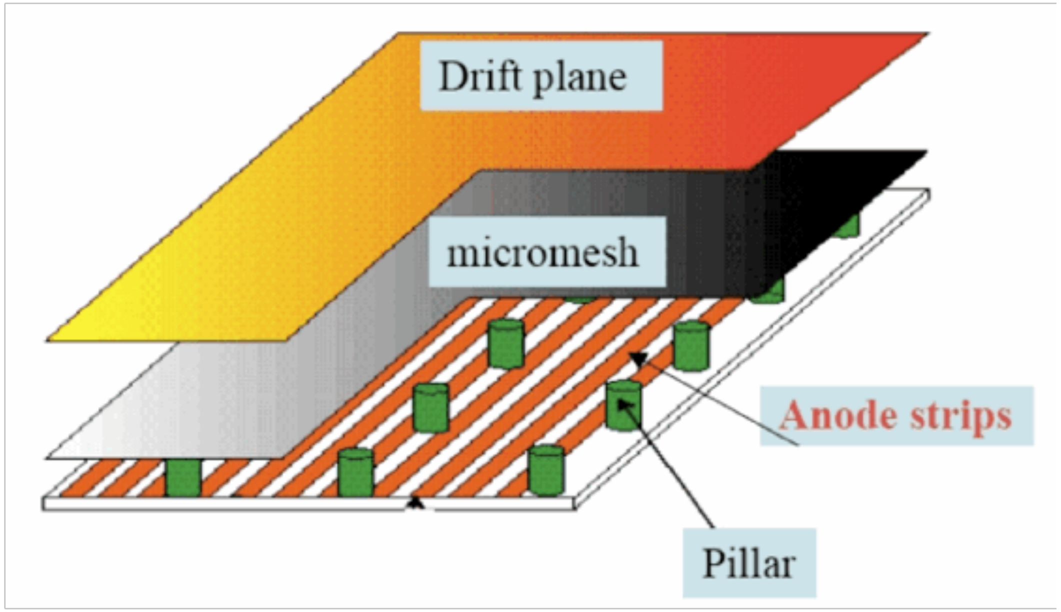
Micro-Pattern Gas Detectors

- a number of developments were started, some with a lot of problems
- two technologies are currently the most successful: GEMs and MicroMegas

- MicroMegas: Avalanche amplification in a small gap

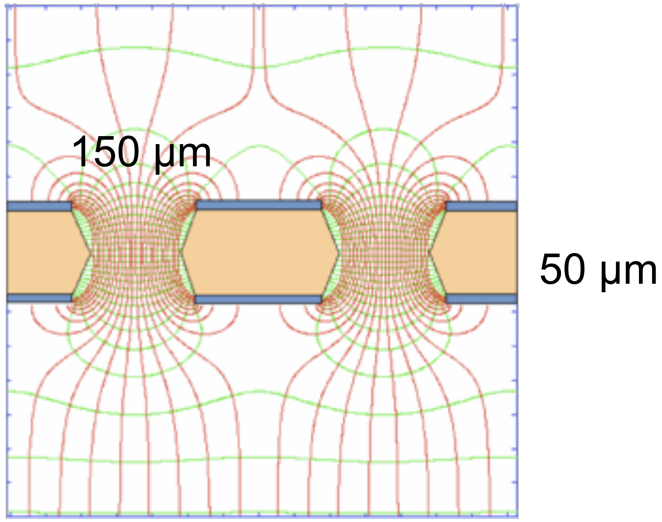
Y. Giomataris et al, NIM A376, 29(1996)

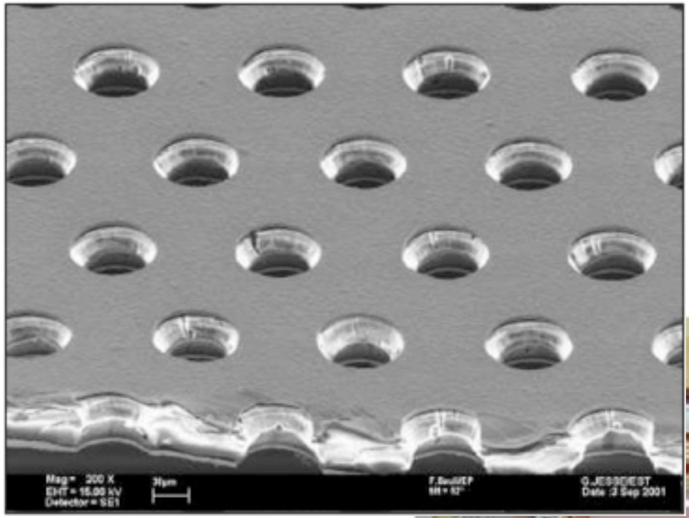


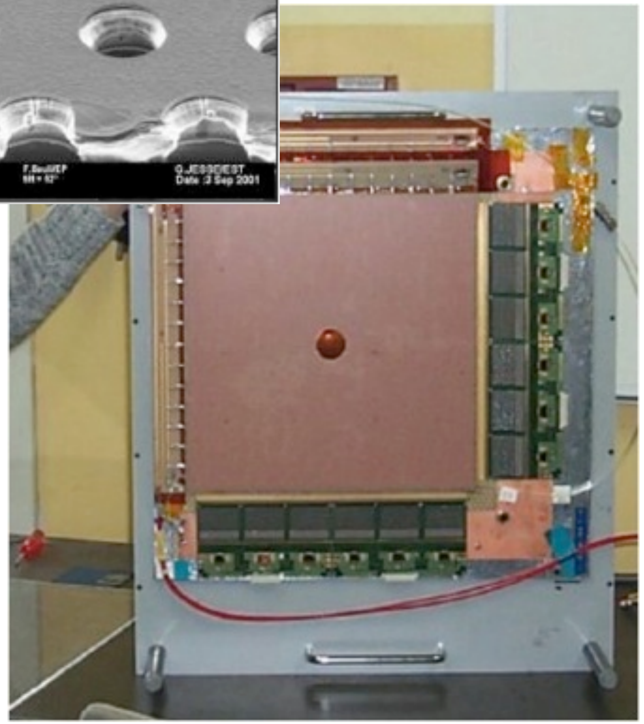


New Developments

- GEM: Gas Electron Multiplier: Gas amplification in small holes in a special foil







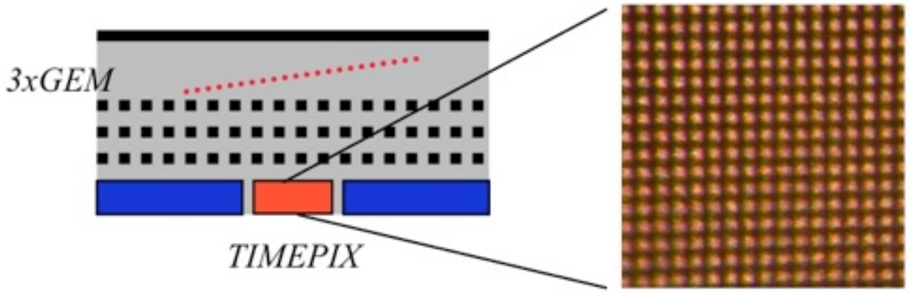
Charge collection on two separate levels: 2D structure possible: separation of amplification and read out

Both technologies, MicroMegas and GEMs are used in experiments. Typical spacial resolution: ~70 um

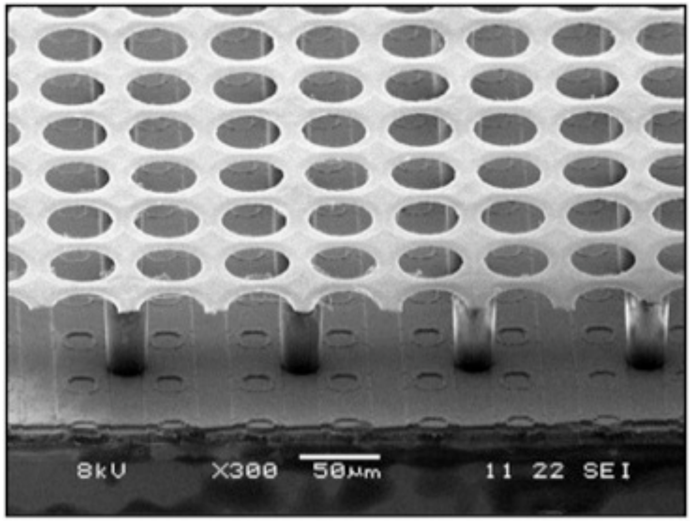
F. Sauli, NIM A386, 531(1997)

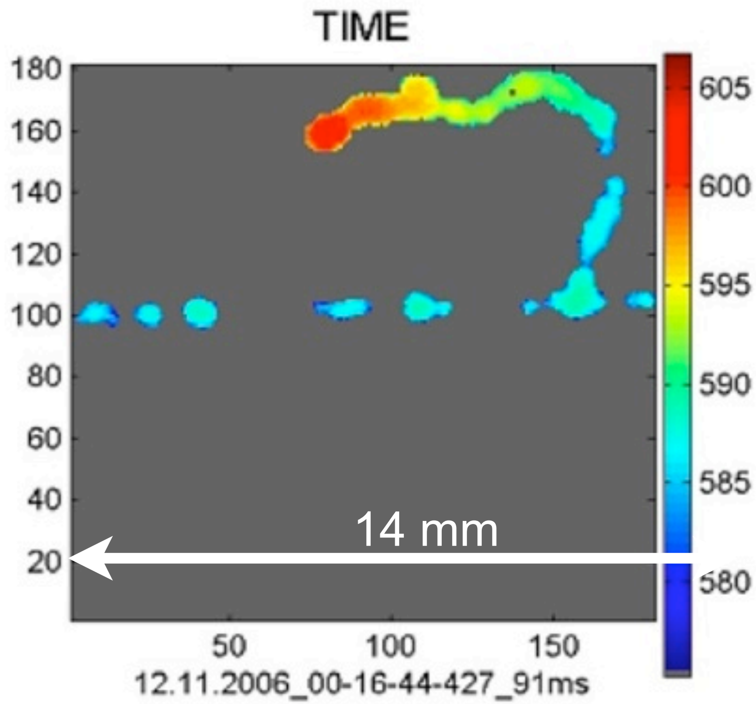
MPGDs as next generation detector

- Combination of gas detectors and Silicon
  - Integration of MPGDs with pixel read out chips



- Amplification and read out made of silicon





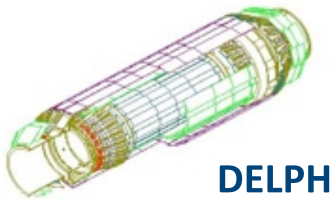
Advantages of gas detectors:

- Low radiation length
- Gas can be replaced regularly: Reduction of radiation damages!

V.b Semiconductor-Detectors

Large Silicon Systems

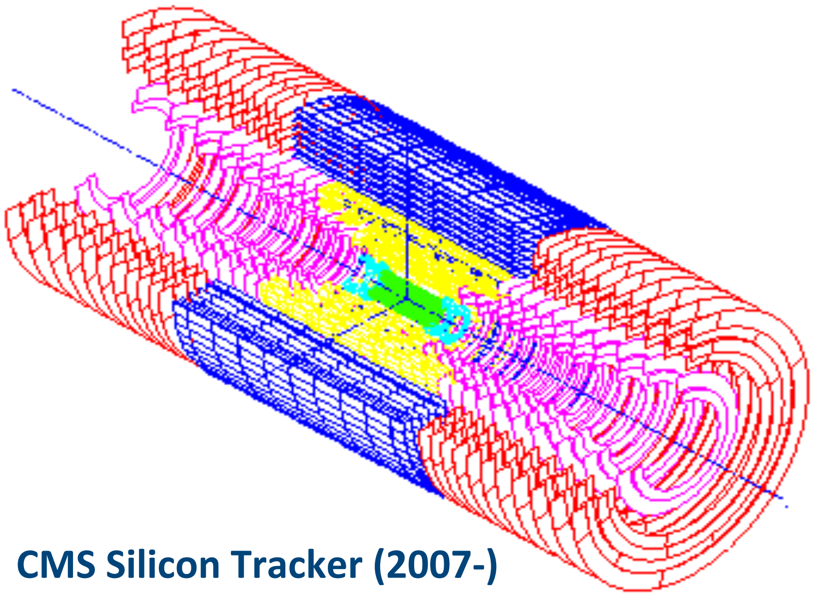
Since ~ 30 years: Semiconductor detectors for precise position measurements.



DELPHI (1996)

~ 1.8m^2 silicon area

~ 175 000 readout channels



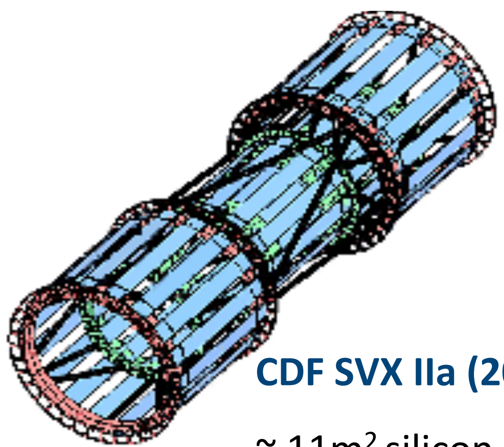
CMS Silicon Tracker (2007-)

~12,000 modules

~ 223 m^2 silicon area

~25,000 silicon wafers

~ 10M readout channels



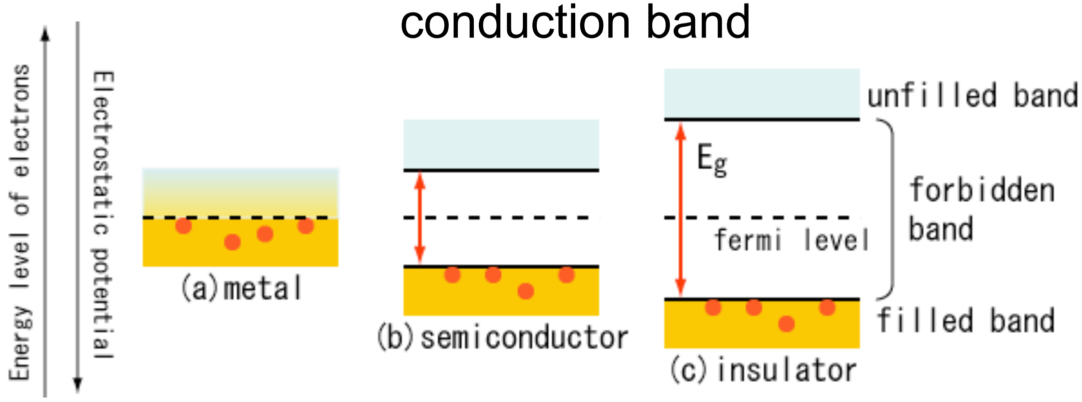
CDF SVX IIa (2001-2012)

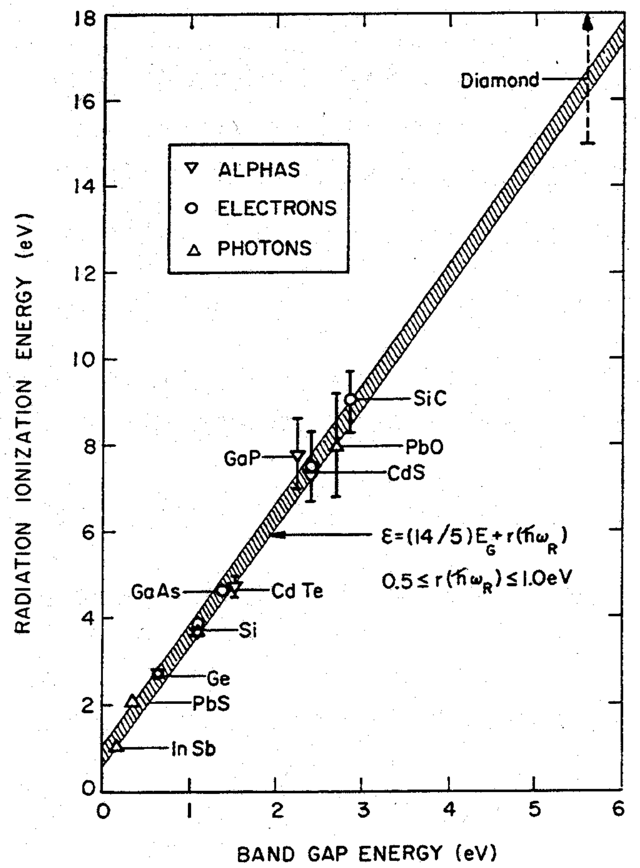
~ 11m^2 silicon area

~ 750 000 readout channels

Semiconductor Basics I

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



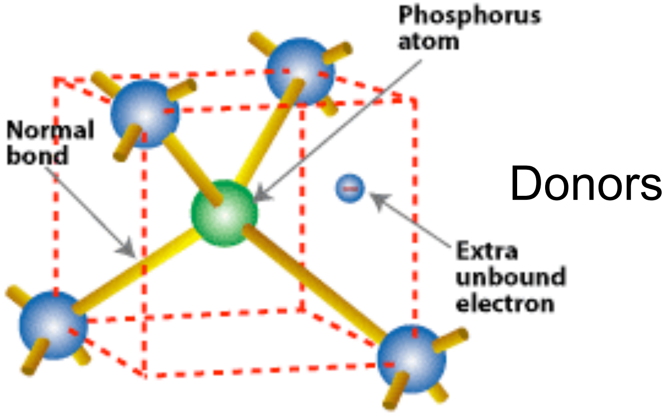


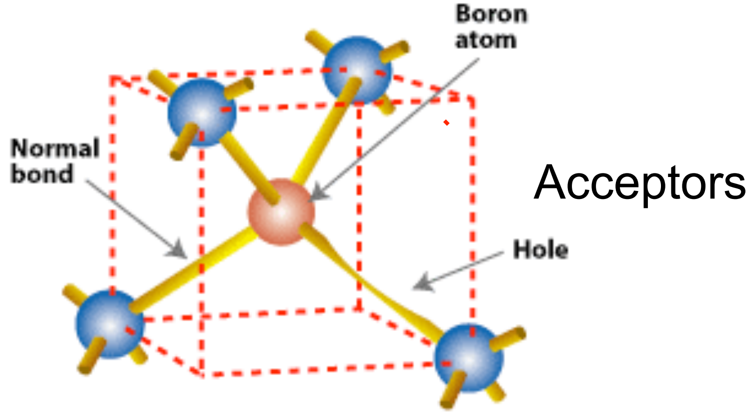
C.A. Klein, J. Applied Physics 39 (1968) 2029

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

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

Doping Silicon





n-type:

- In an n-type semiconductor, negative charge carriers (electrons) are obtained by adding impurities of donor ions (eg. Phosphorus (type V))
- Donors introduce energy levels close to conduction band thus almost fully ionized

Electrons are the majority carriers.

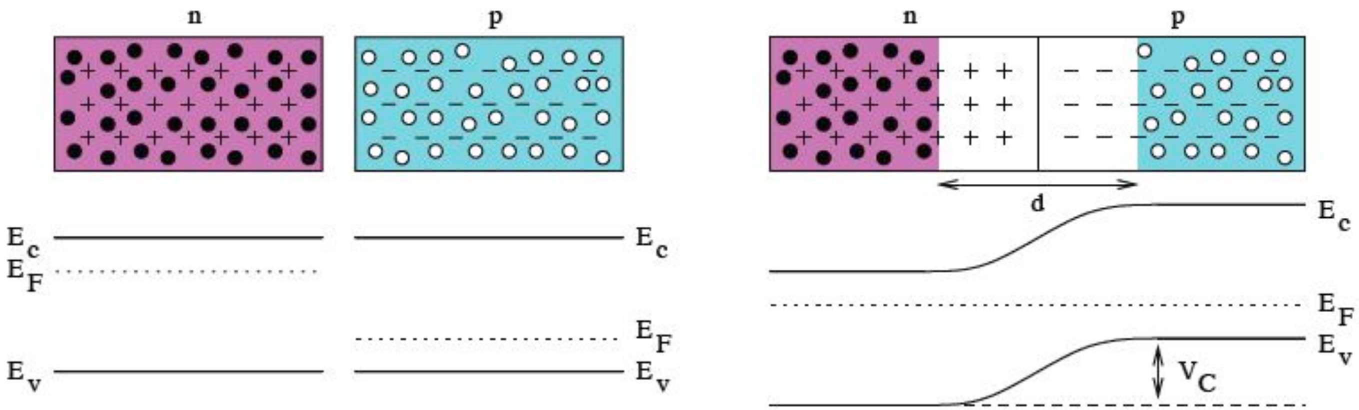
p-type:

- In a p-type semiconductor, positive charge carriers (holes) are obtained by adding impurities of acceptor ions (eg. Boron (type III)).
- Acceptors introduce energy levels close to valence band thus 'absorb' electrons from VB, creating holes

Holes are the majority carriers.

PN-Junction

- p- and n-doted semiconductor combined
- Gradient of electron and hole densities results in a diffuse migration of majority carriers across the junction.
- Migration leaves a region of net charge of opposite sign on each side, called the depletion region (depleted of charge carriers).



- Artificially increasing this depleted region by applying a **reversed bias voltage** allow charge collection from a larger volume

$$d = \sqrt{\frac{2\epsilon\epsilon_0 V}{e}\left(\frac{1}{n_D} + \frac{1}{n_A}\right)} \quad \text{with} \quad n_A >> n_D \quad d = \sqrt{\frac{2\epsilon\epsilon_0 V}{e n_D}}$$

Principle of Semiconductor Detectors

1. Creation of electric field: voltage to deplete thickness d

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

$N_{\rm eff}$: doping concentration

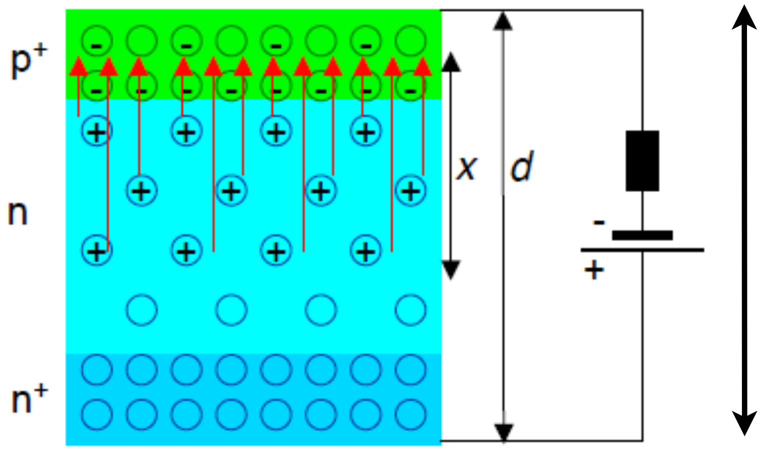
2. Keep dark current low

$$I \propto \frac{1}{\tau_g} \cdot T^2 \cdot \exp^{-\frac{E_g}{2kT}} \times \text{volume}$$

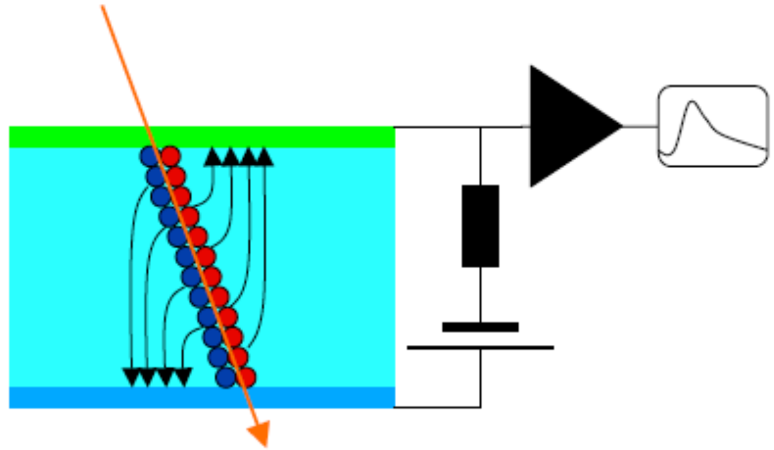
τ_g : charge carrier life time

3. Ionizing particles create free charge carrier

4. Charge carrier drift to electrodes and induce signal

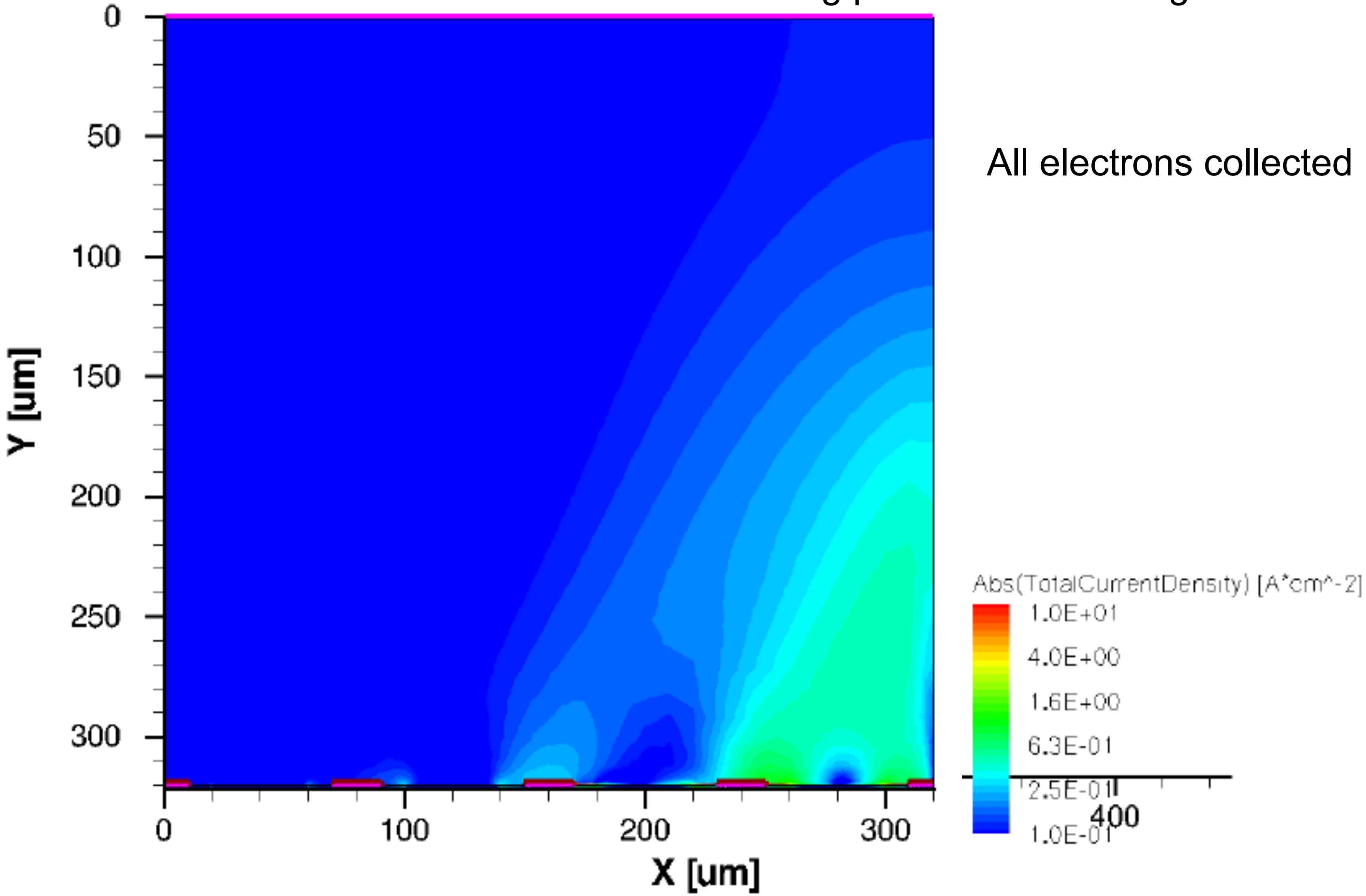


in "classical" HEP detectors 100-300 um



Current Density

Ionizing particle with 45° angle t=7ns



All electrons collected

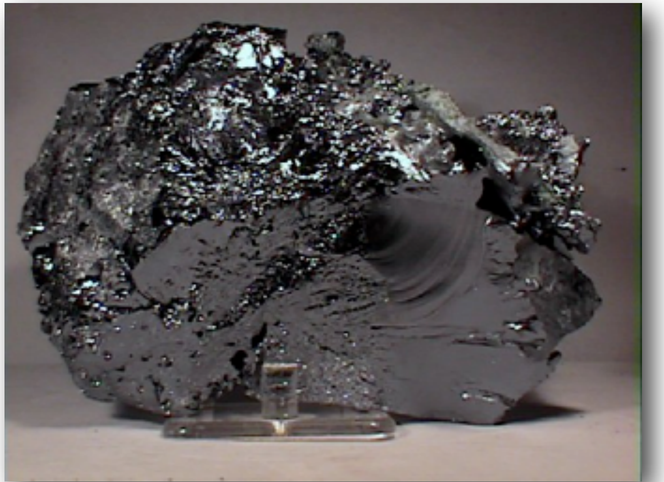
Simulation: Thomas Eichhorn

Material Properties

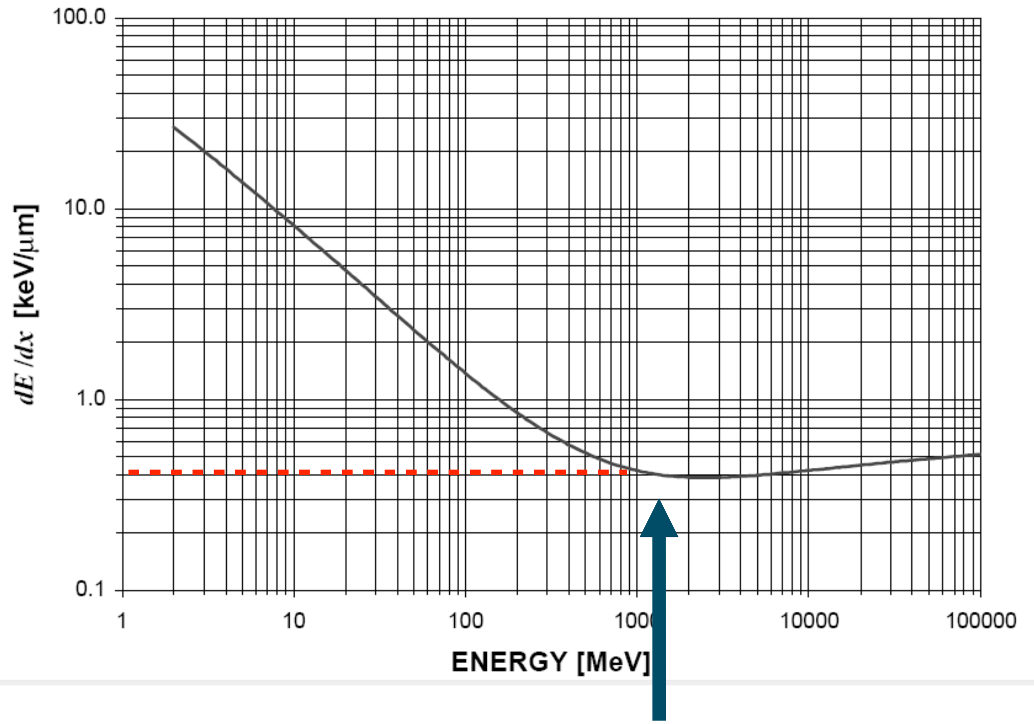
	Si	Ge	GaAs	CdTe	Diamant	SiC
band gap	1.12	0.67	1.42	1.56	5.48	2.99
energy for e-p pair [eV]	3.6	2.9	4.2	4.7	13.1	6.9
e- for MIP (300µm)	24000	50000	35000	35000	9300	19000
Z	14	32	31+33	48+52	6	14+6

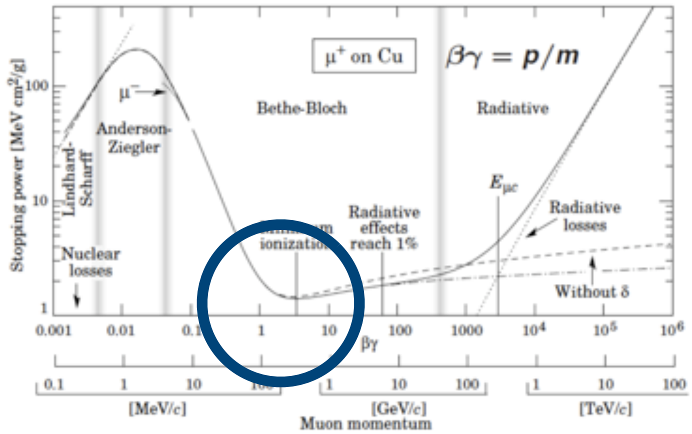
Why is silicon used more often ?

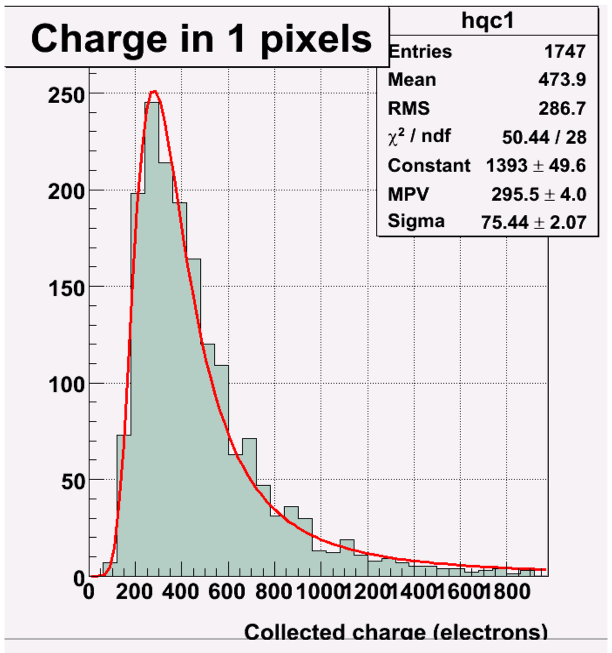
- Silicon is the only material which can be produced in larger areas in high quality
- compare to kT = 0.026 eV at room temperature -> dark current under control
- high density compared to gases: ρ=2.33g/cm^3
- good mechanical stability -> possible to produce mechanically stable layers
- large charge carrier mobility
- fast charge collection $\delta t \sim$10ns
- well understood -> radiation tolerant



Protons in Silicon



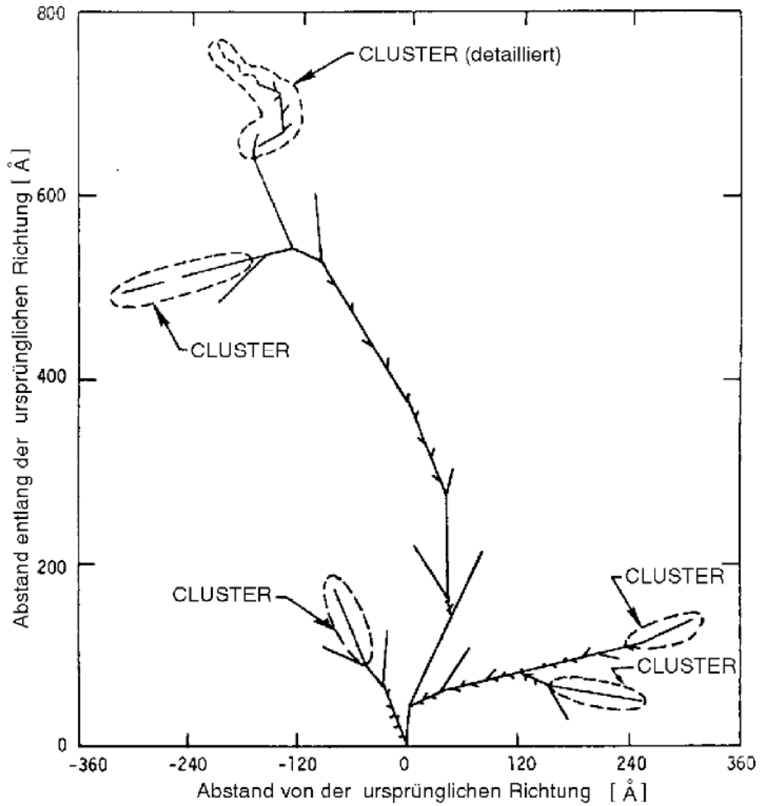




- 0.4 keV/µm
- -> 3.6 eV creates electron hole pair
- => ~110 electron-hole pairs per µm (mean value)
- most probably number: 80 electrons

Problem: Radiation Damage

- Impact of Radiation on Silicon:
- Silicon Atoms can be displaced from their lattice position
- Point defects (EM Radiation)
- Damage clusters (Nuclear Reactions)
- Important in this context:
  - Bulk Effects: Lattice damage: Generation of vacancies and interstitial atoms (NIEL: Non Ionizing Energy Loss) **(main problem for sensors)**
  - Surface effects: Generation of charge traps (Oxides) (by ionizing energy loss) **(main problem for electronics)**



Filling of energy levels in the band gap

➪ direct excitation now possible

➪ higher leakage current

➪ more noise

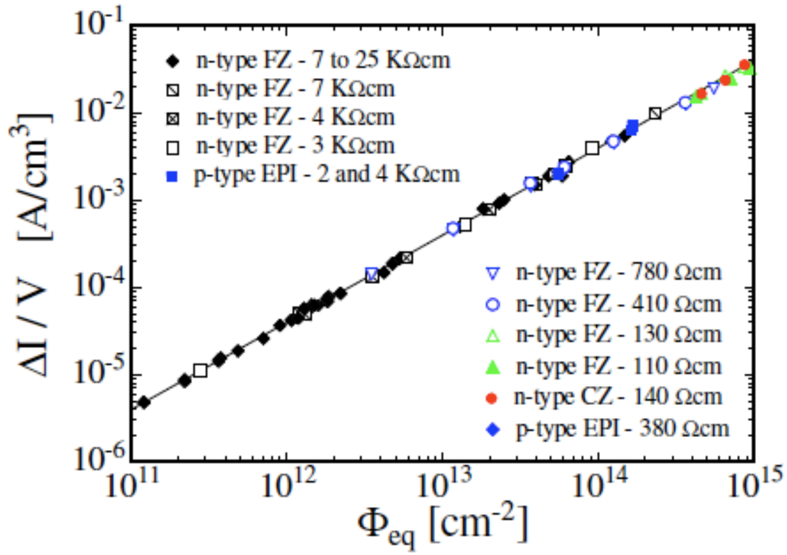
➪ "Charge trapping", causing lower charge collection efficiency

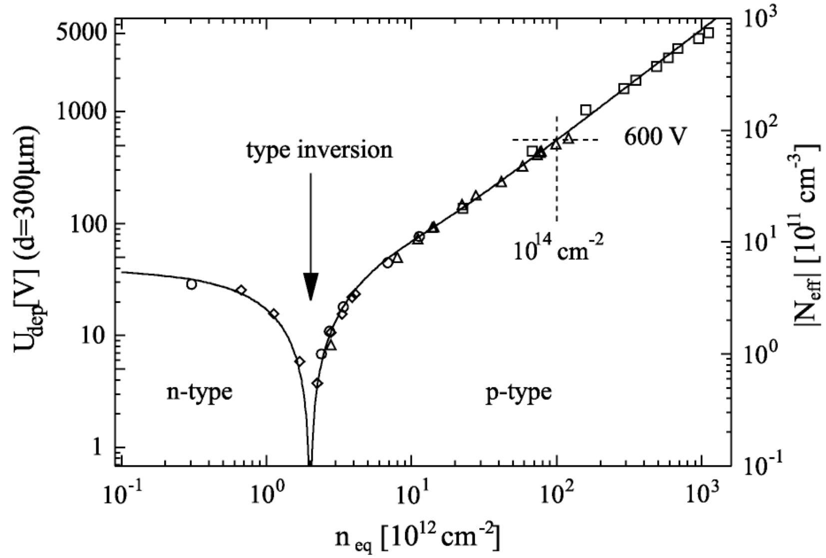
Can also contribute to space charge: Higher bias voltage necessary.

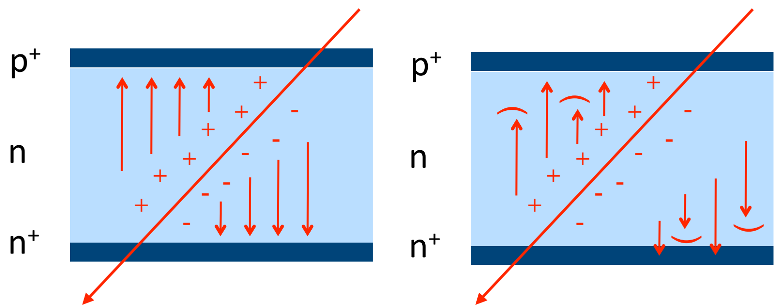
very complex topic ….

Consequences of Radiation Damage

Macroscopic constant: leakage current and depletion voltage







Charge trapping in defects

Counter measures

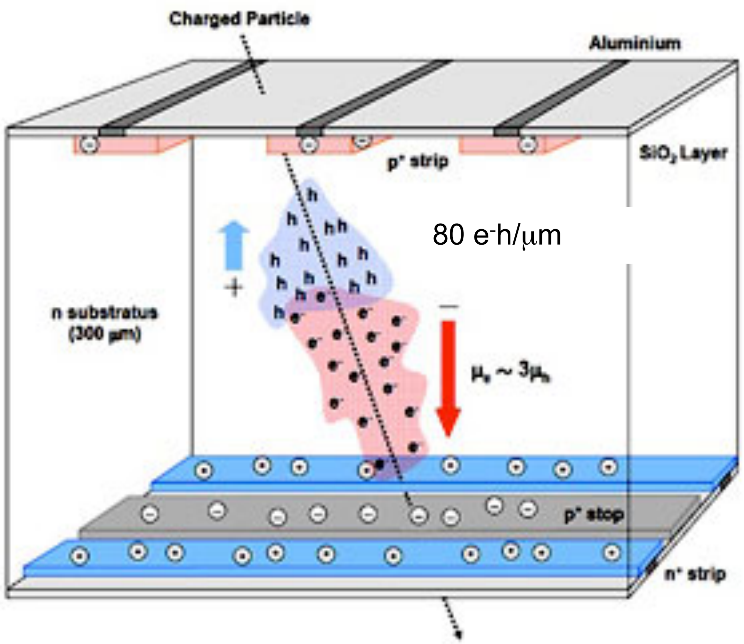
- Geometrical: develop sensors that can withstand higher depletion voltages
- Thinner sensors (but FE electronics with higher sensitivity needed)
- Environment: sensor cooling (~-10 C)
- Slowing down of “reverse annealing”
- Lower leakage currents

Coffee Break ??

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 25 years

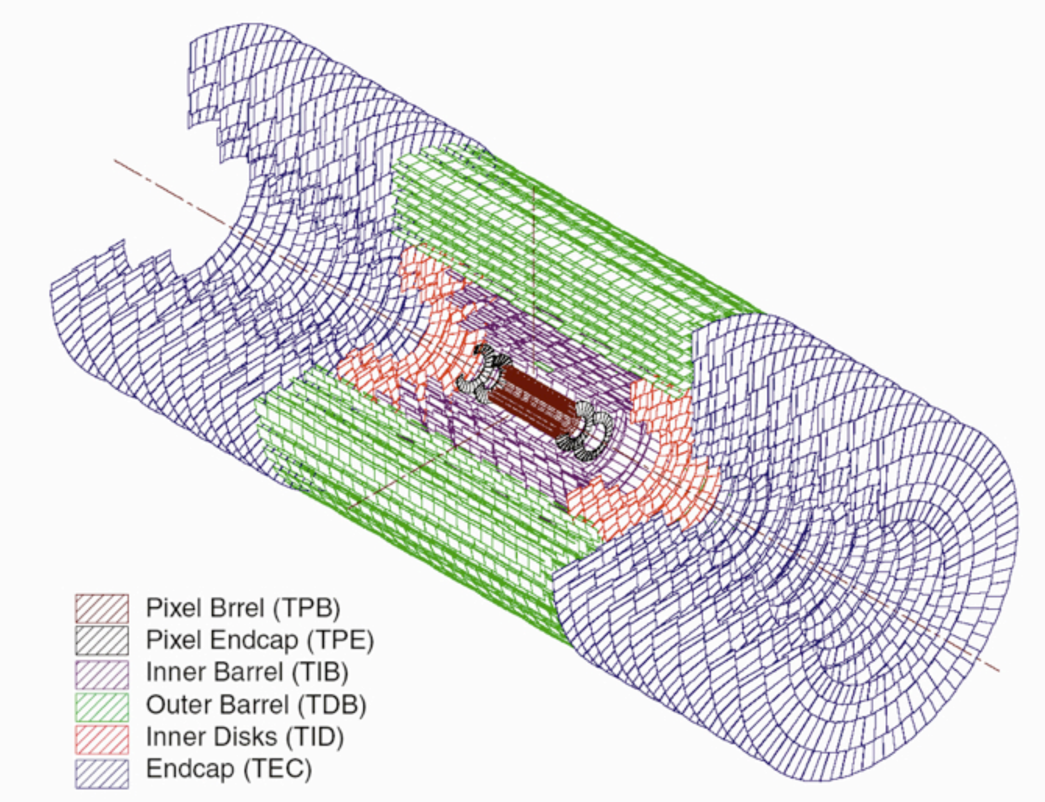
Pic: AMS Collaboration



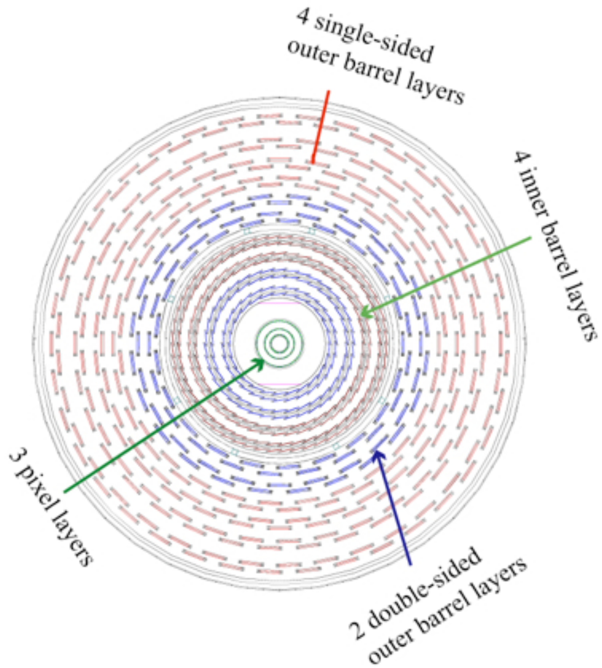
Principle: Silicon strip detector

- Arrangement of strip implants acting as charge collecting electrodes.
- Form a one-dimensional array of diodes (on a low doped fully depleted silicon wafer these)
- By connecting each of the metallised 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)

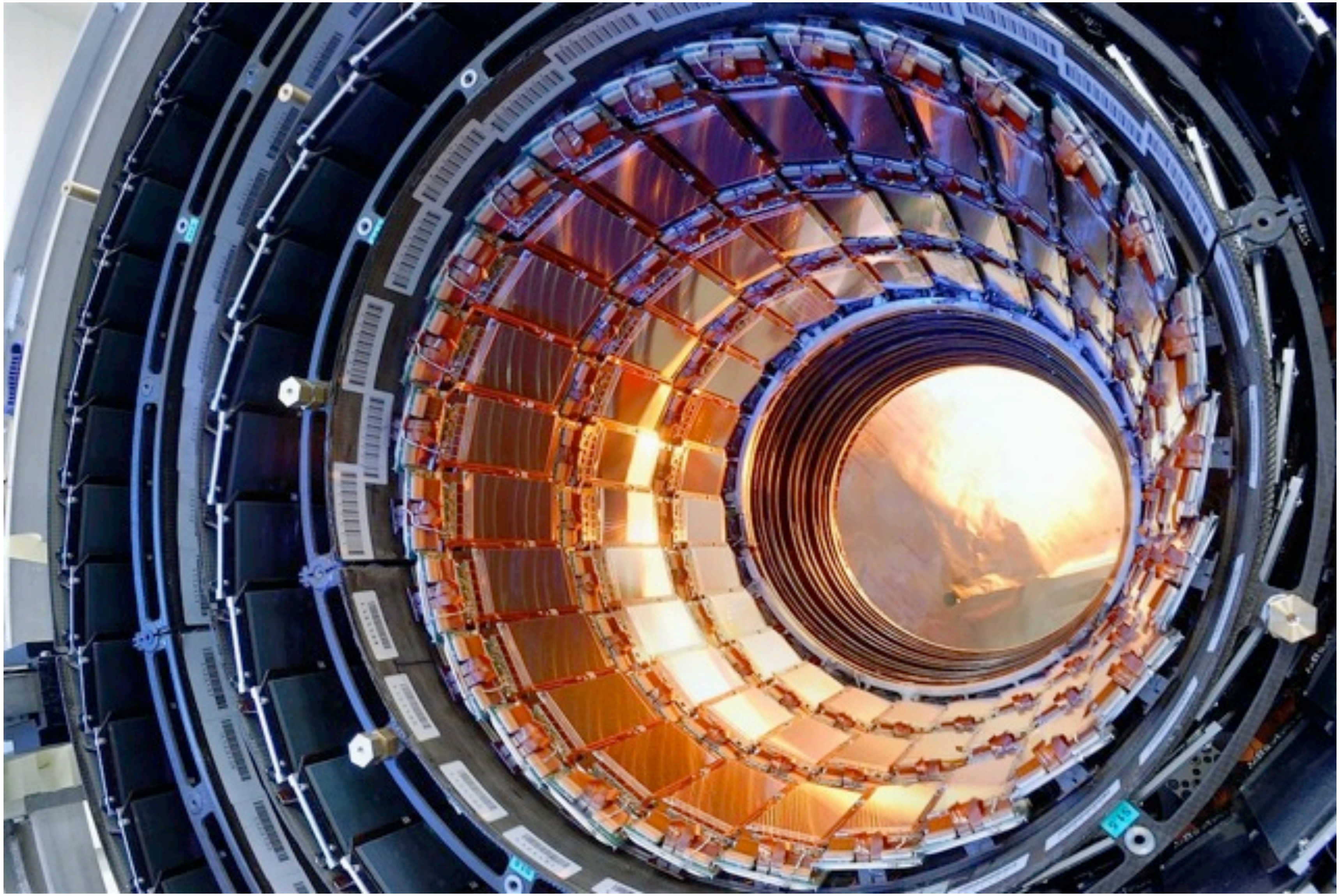
CMS Si-Tracker



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

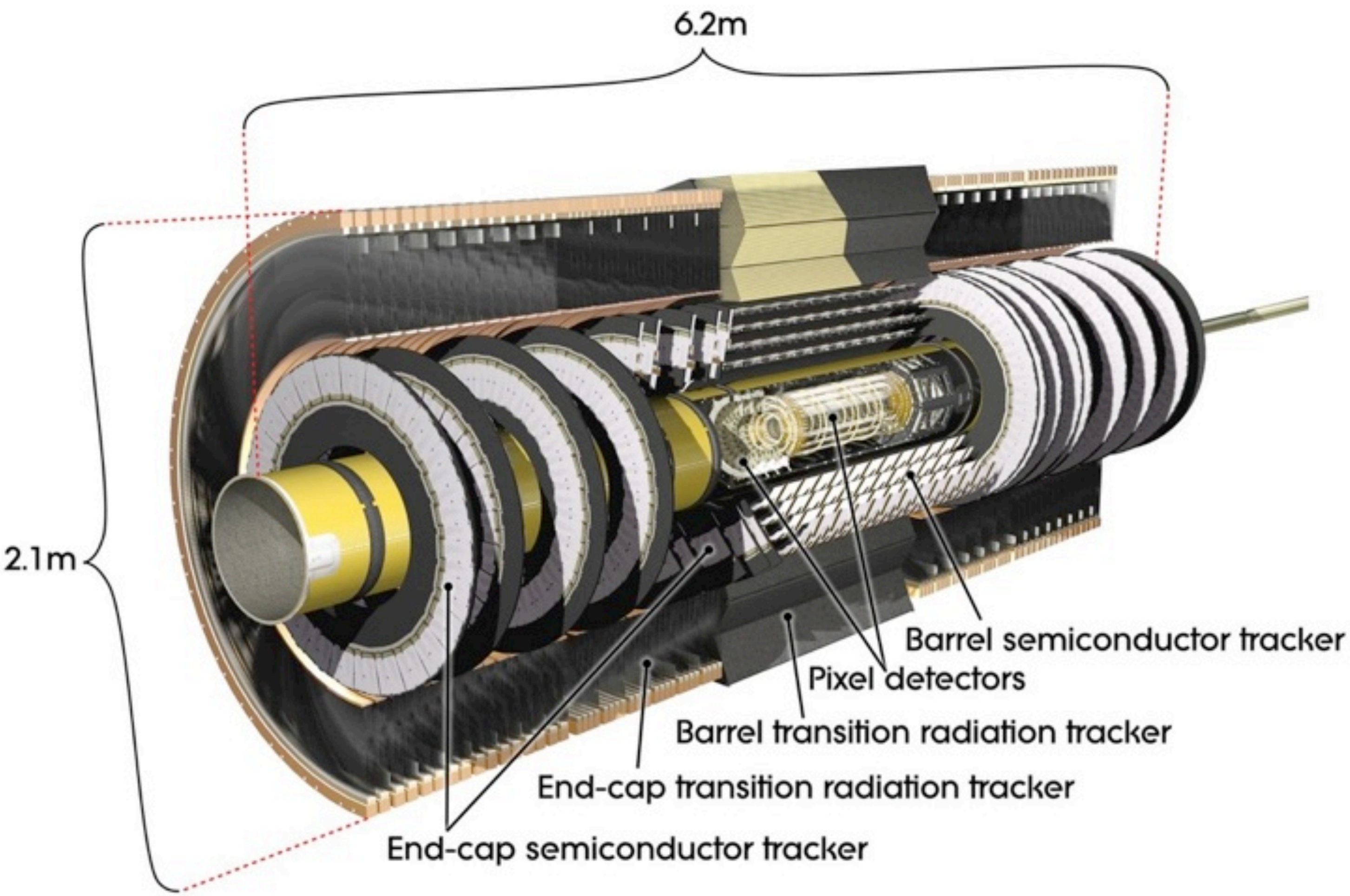


CMS Tracker - Beauty Shot



Pic: CERN

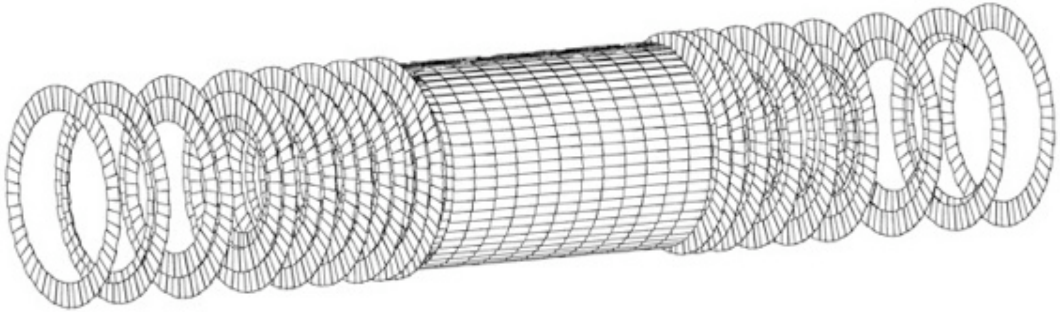
ATLAS SCT

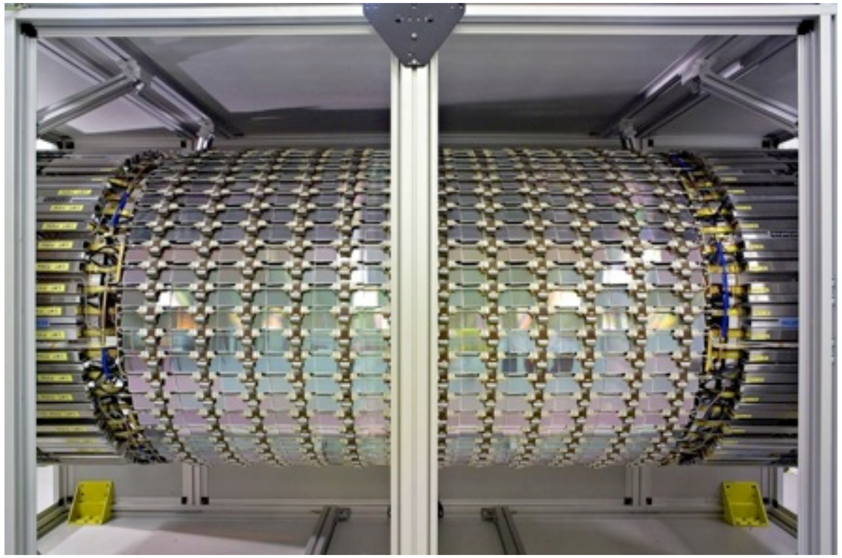


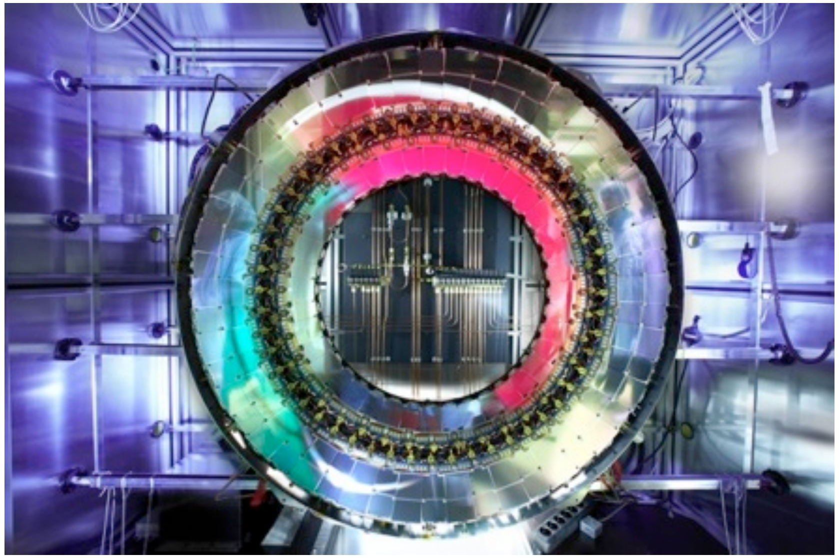
- ATLAS Si-Detector SCT:
  - Si- strips: 4 Barrel-layer, 2 x 9 discs

ATLAS SCT

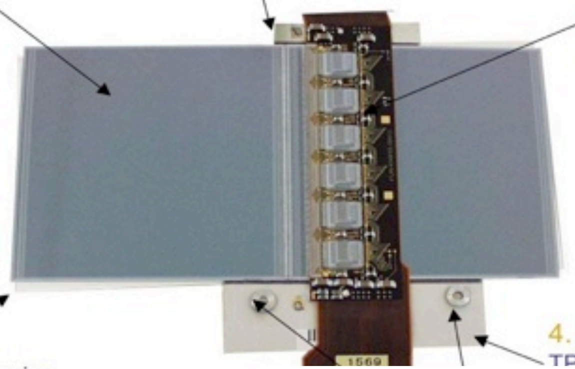
- SCT strips:
  - 61 m^2 silicon, ~6.2 M channels
  - 4088 modules, 2112 barrel (1 type), 1976 in the discs (4 different types)

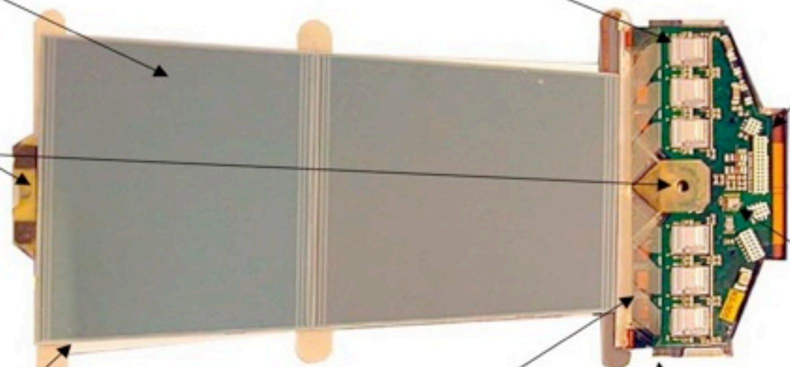




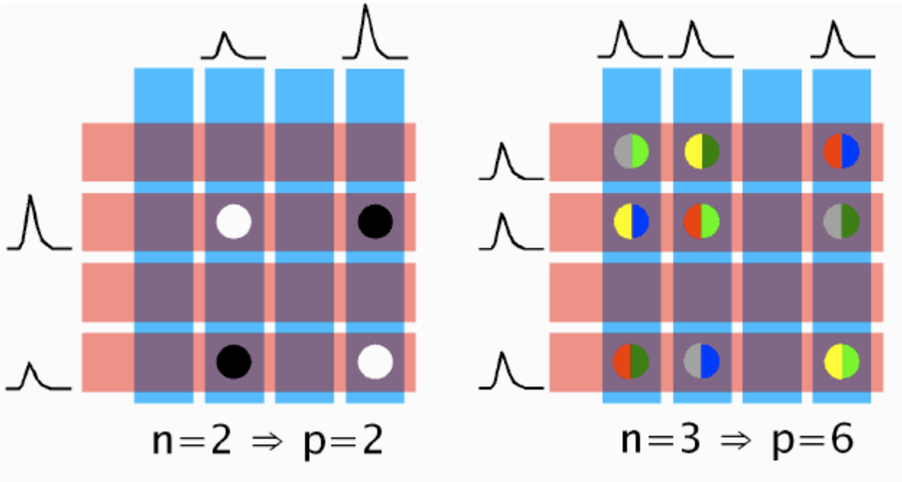


Example: ATLAS SCT Module

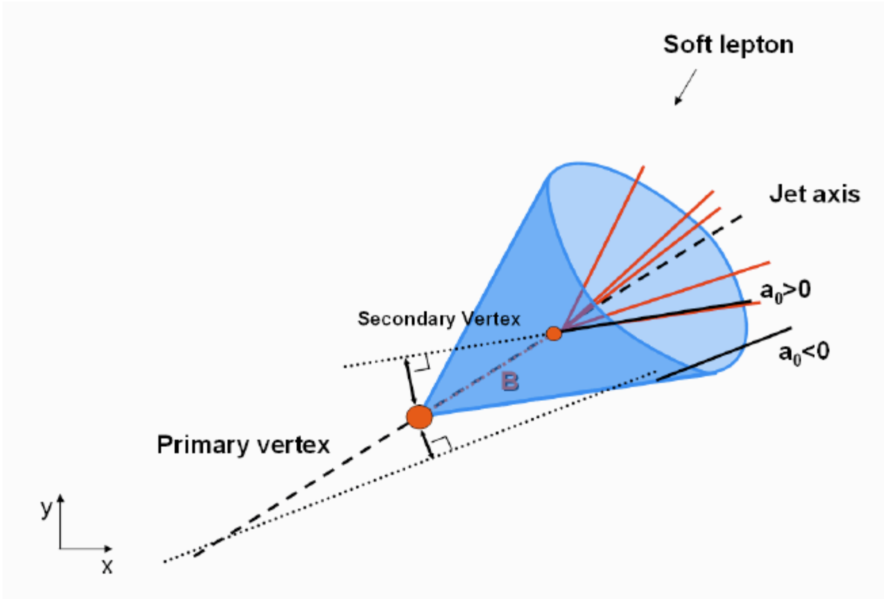




Limits of Strip Detectors



- 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

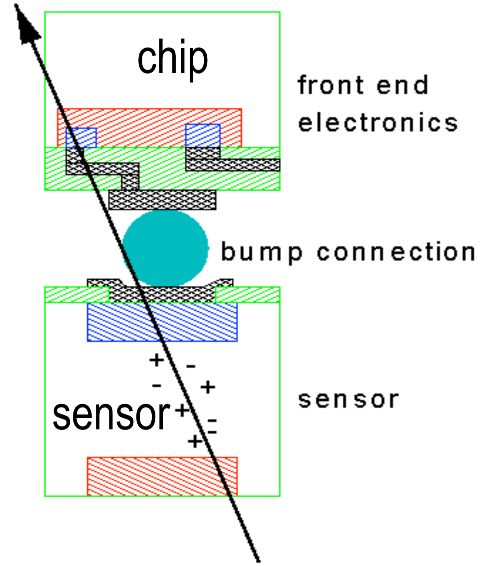
First pixels (CCDs) in NA11/NA32: ~1983

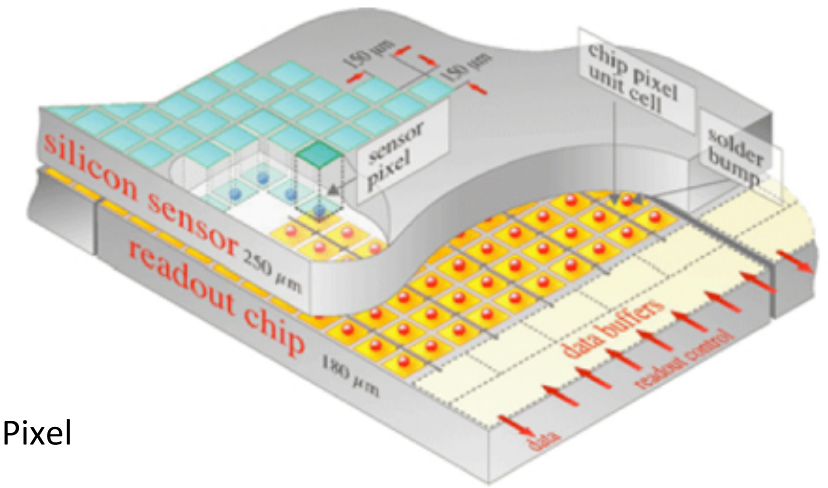
Hybrid Pixels – "classical" Choice HEP

- 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

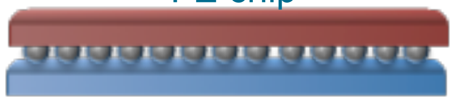




Hybrid Pixel
(CMS)

- 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
- ….

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

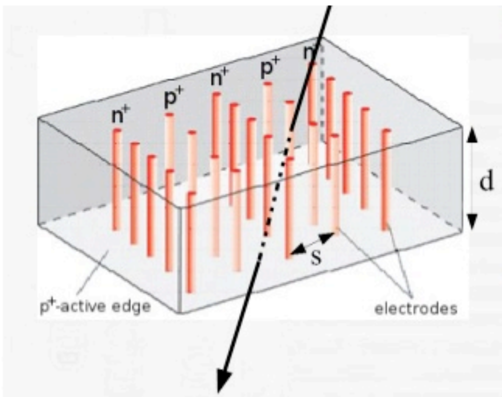
3D Silicon

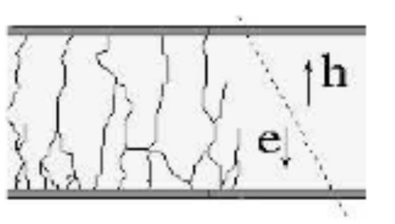
- Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Low charge sharing

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)

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

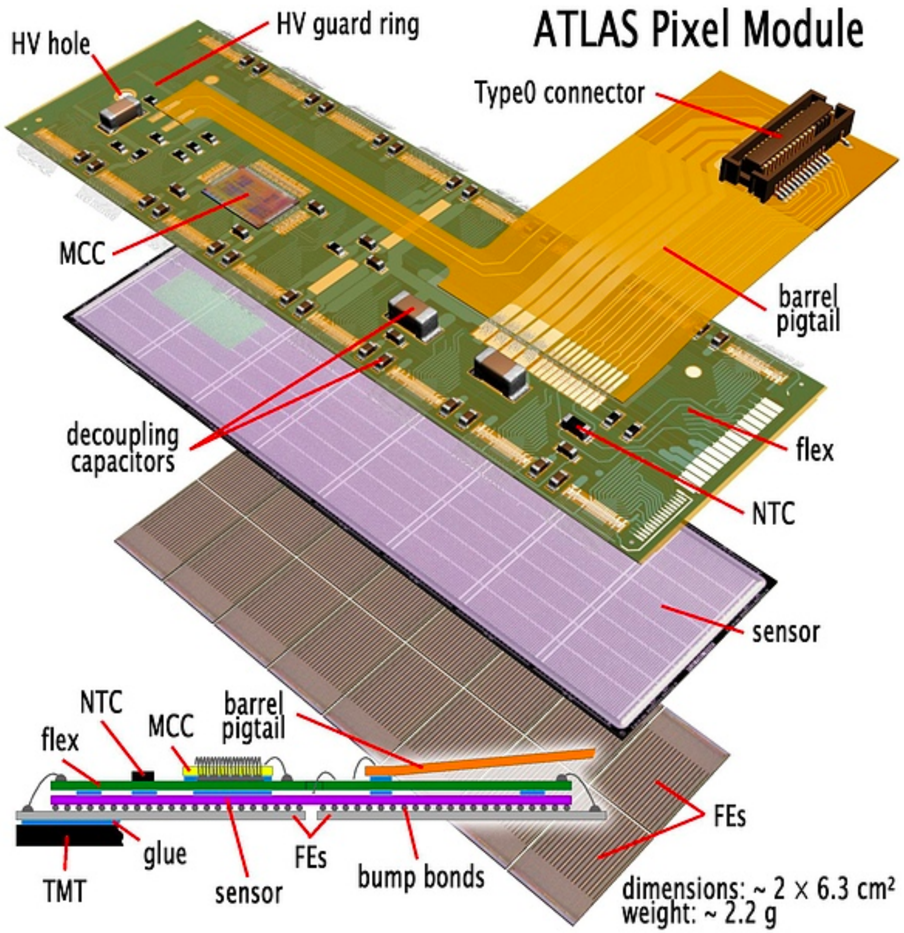




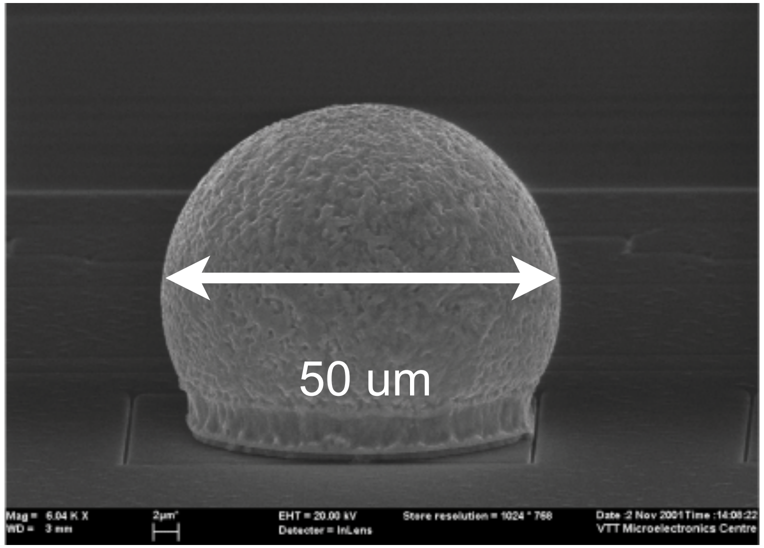
ATLAS-Pixels

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

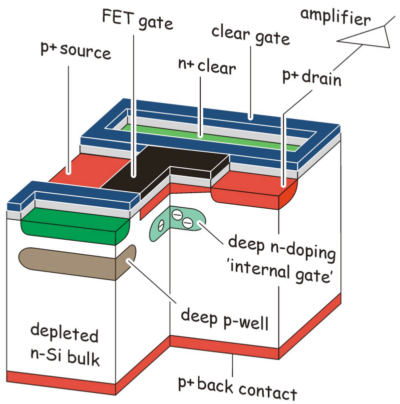


Picture: VTT

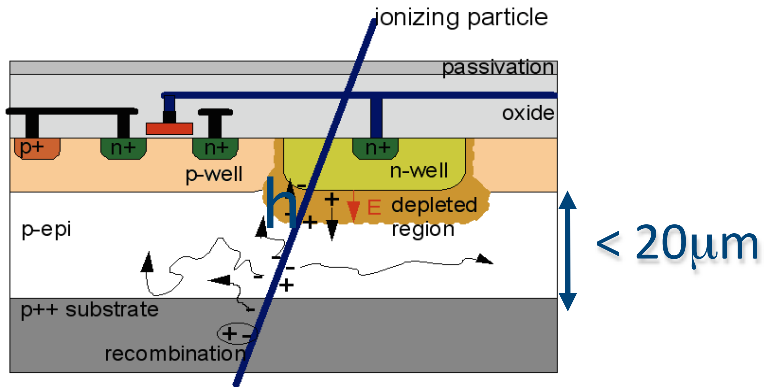


Monolithic Pixel Sensors

- 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 which have sensor and readout electronics in one layers -> monolithic approach
- Four different technologies under study for ILC vertex detector
  - 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)

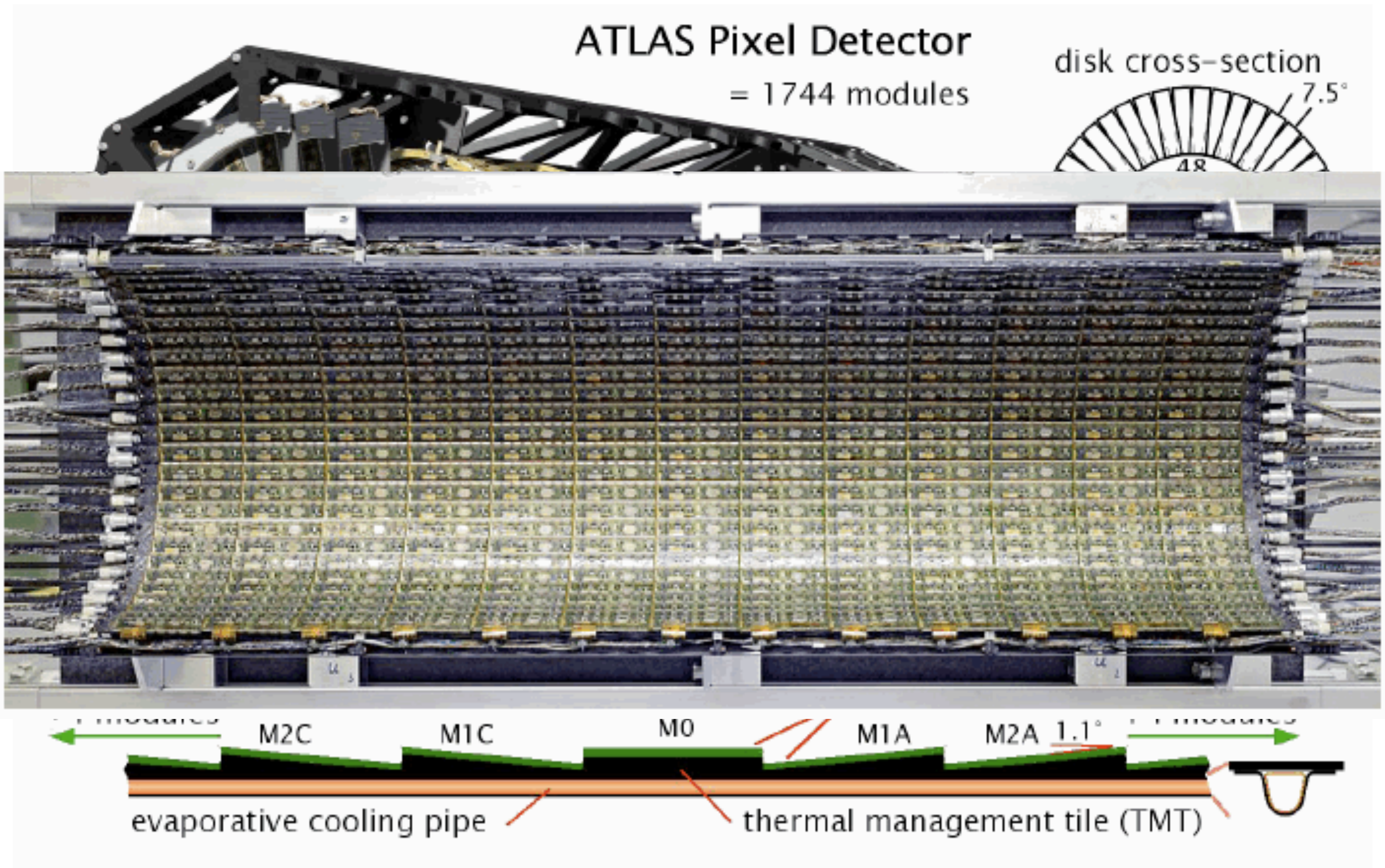


DEPFET



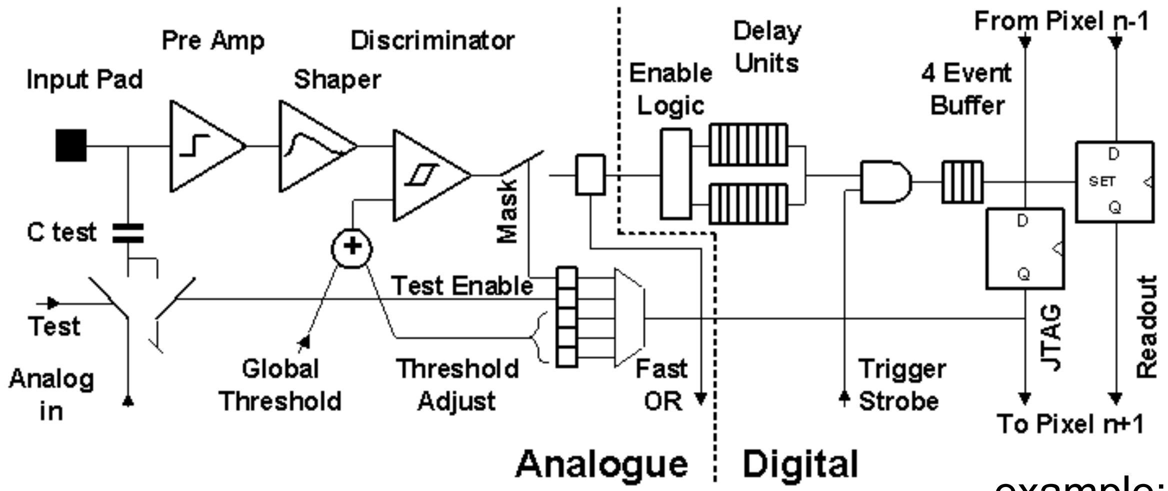
Mimosa MAPS

ATLAS-Pixels



Overview of readout electronics

- Most front-ends follow a similar architecture

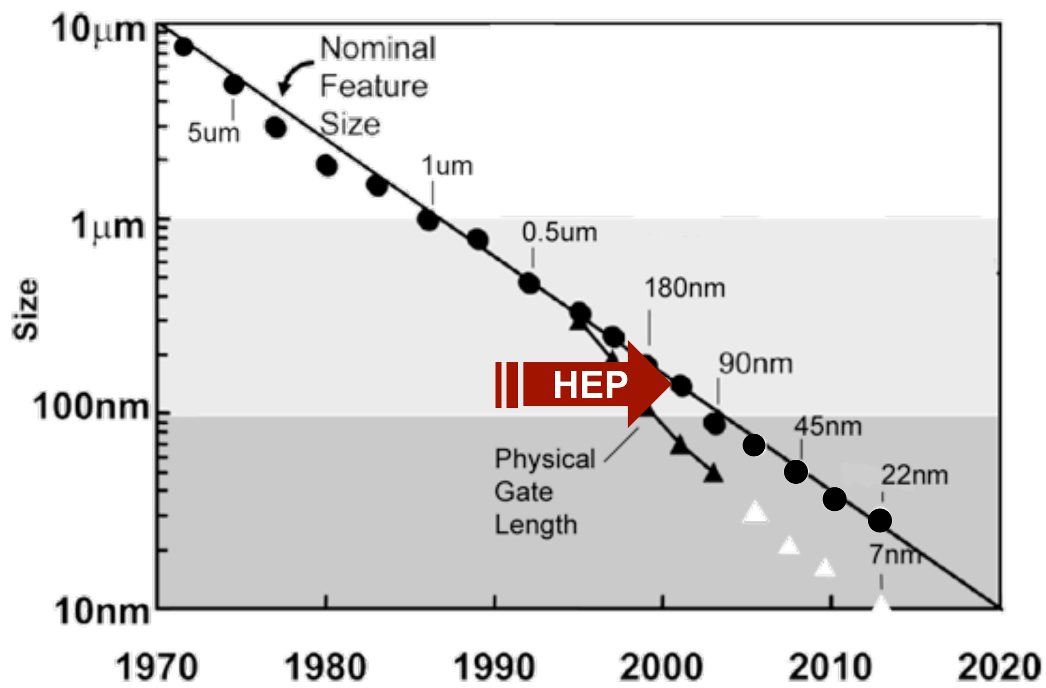


example: ALICE Pixel detector

- 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

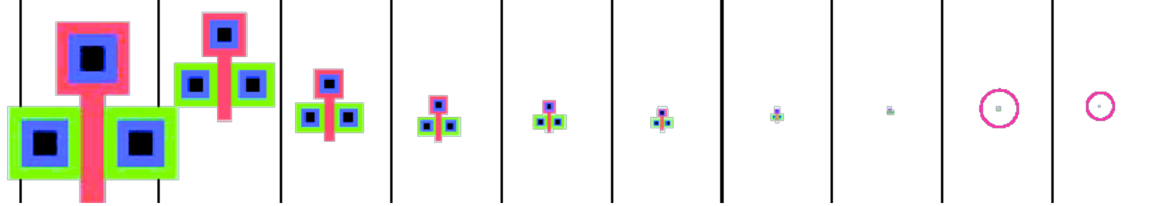
Industry Scaling Roadmap

- 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 sets limits
- HEP nowadays at 90nm and 130nm
- Problem: by the time a technology is ready for HEP -> “old” in industry standards

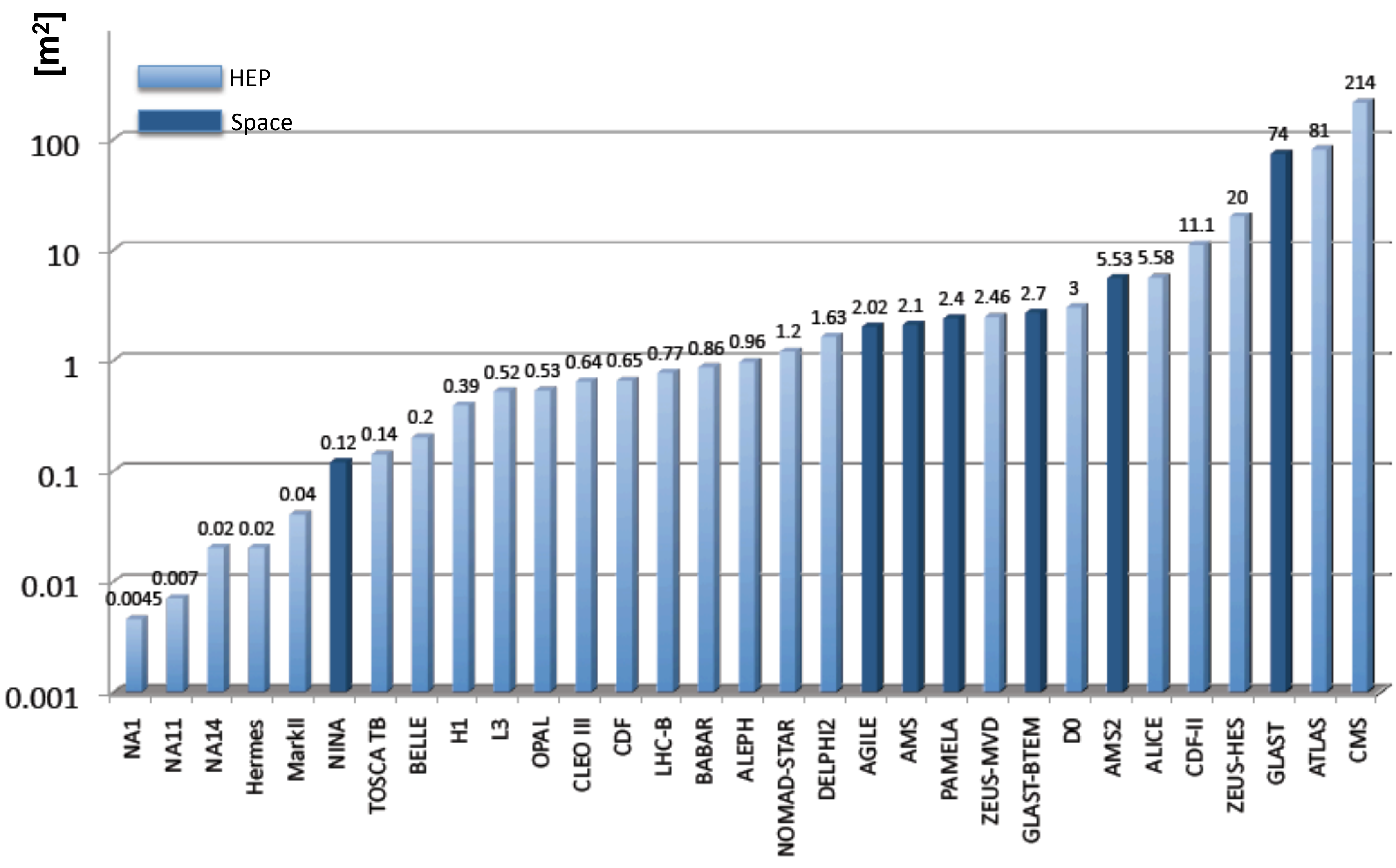


Feature Size [nm]	2000	1200	800	500	350	250	130	65	35	20

Minimum NMOS



Silicon detector size 1981 - 2006



Summary Part 3

- Tracking detectors are playing an important role in HEP since the late 50ties
- Starting with bubble chamber the development of tracking detectors was rather rapidly
- Modern gas detectors and silicon trackers play an equal important role in HEP; in HL-LHC the focus will be on silicon trackers
- The technologies are rapidly evolving giving hope to have really fancy detectors for example for the future LC