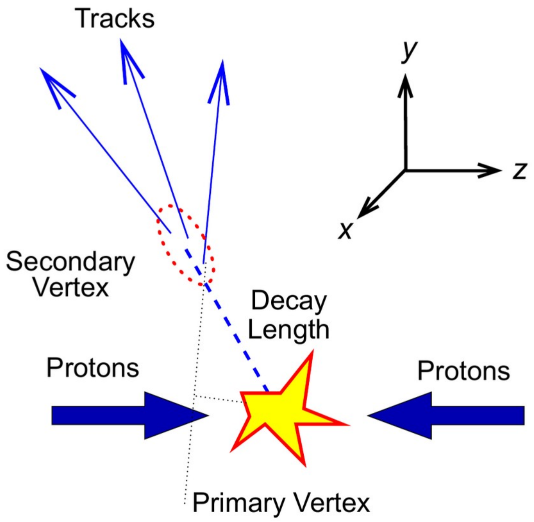
Part 3, Lecture 3: Tracking Detectors

Olaf Steinkamp

Tracking Detectors

Measure the trajectories of long-lived charged particles

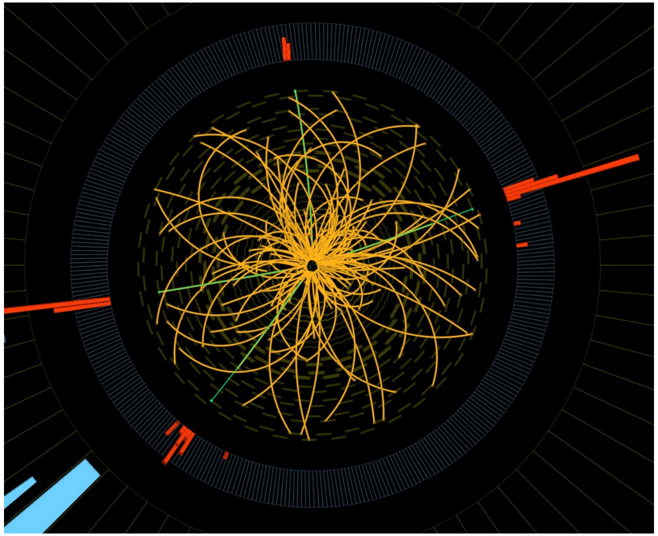
- determine the origin of the particle: was it produced
  → directly in the collision of the beam particles ("primary vertex")
  → or in the decay of a short-lived particle ("secondary vertex")
- determine its direction of flight
- determine its momentum from the bending of its trajectory in a magnetic field
- link to the other parts of the detector, e.g.
  → particle showers reconstructed in calorimeters
  → photons measured in Cherenkov detectors



Momentum measurement

Determine the momentum of long-lived charged particles from the curvature of their trajectory in a magnetic field

$$\left.\begin{aligned} \vec{F}_L &= q \cdot \vec{v} \times \vec{B} \\ \frac{m \cdot v^2}{r} &= q \cdot v \cdot B \end{aligned}\right\} \quad p = q \cdot B \cdot r$$



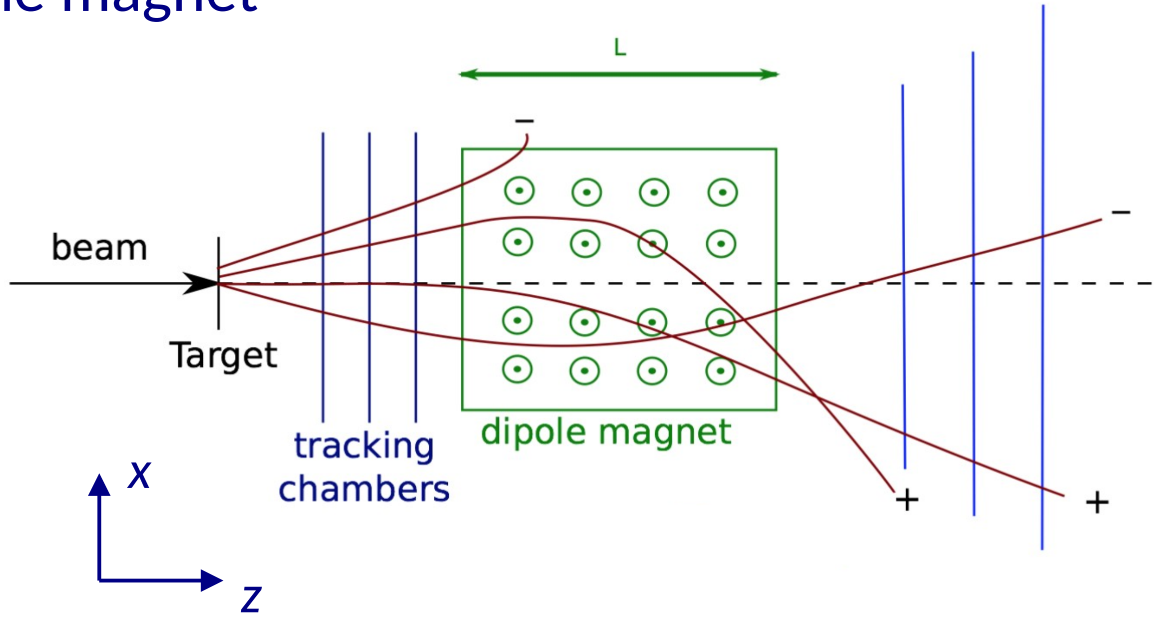
- for $q = \pm 1$:

$$p\,[\mathrm{GeV}/c] = 0.3 \cdot B\,[\mathrm{T}] \cdot r\,[\mathrm{m}]$$

Fixed-target experiment

Dipole magnet, field lines orthogonal to beam direction

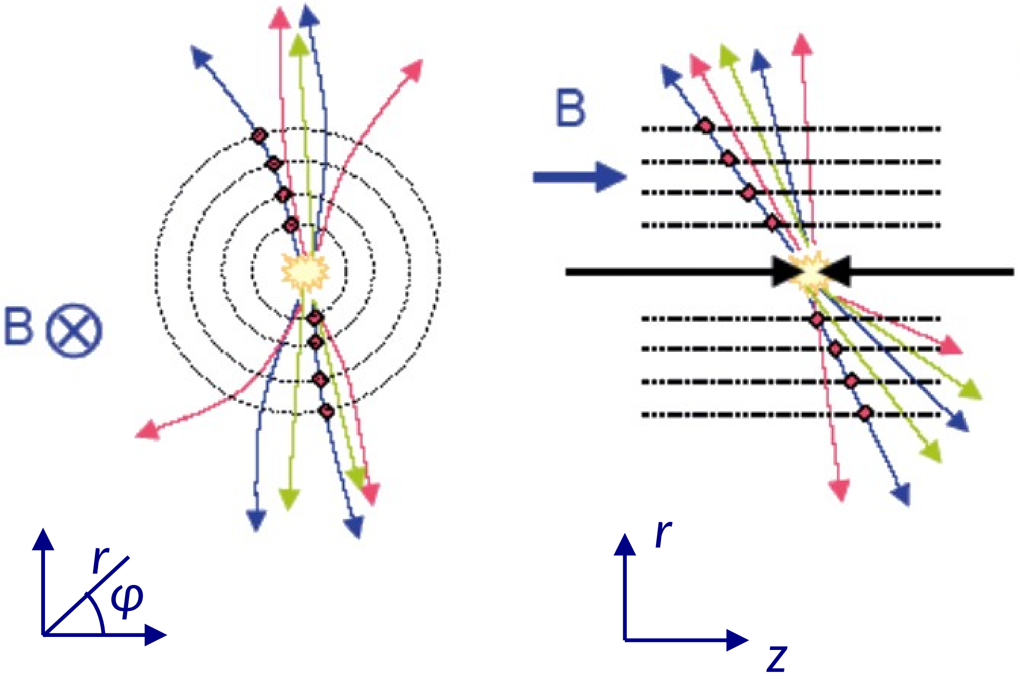
- planar layers of position-sensitive detectors upstream and downstream of the magnet
- measure direction of flight before and after the magnet
- determine momentum from the change in direction in the bending plane of the magnet ("xz plane")



Collider experiment

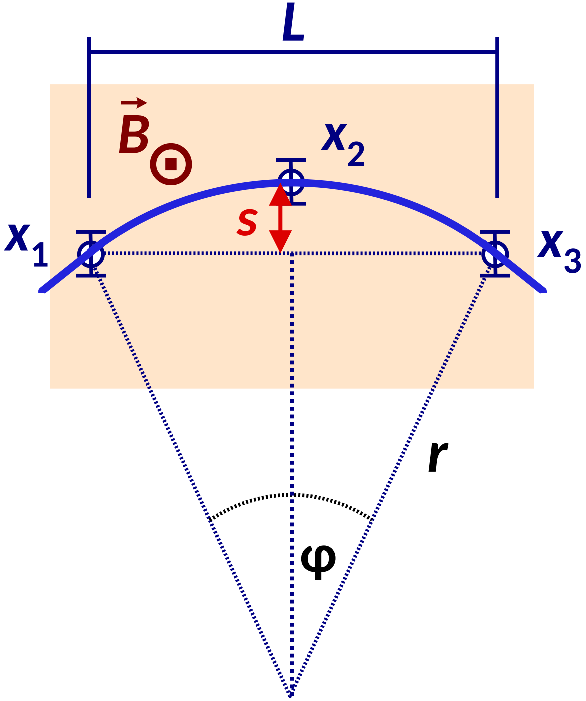
Solenoid magnet with field lines parallel to beam axis

- cylindrical layers of position sensitive detectors inside the magnet
- determine momentum from the bending radius of the trajectory in the plane orthogonal to the beam axis (“r/φ plane”)



Momentum resolution

Simplified example: measure position in three points, determine bending radius from sagitta



- for φ not too large:

$$s = r\cdot\left(1-\cos\frac{\varphi}{2}\right) \approx r\cdot\left[1-\left(1-\frac{1}{2}\left(\frac{\varphi}{2}\right)^2\right)\right] = r\cdot\frac{\varphi^2}{8}$$

$$\frac{L}{2} = r\cdot\sin\frac{\varphi}{2} \approx r\cdot\frac{\varphi}{2} \Rightarrow \varphi = \frac{L}{r}$$

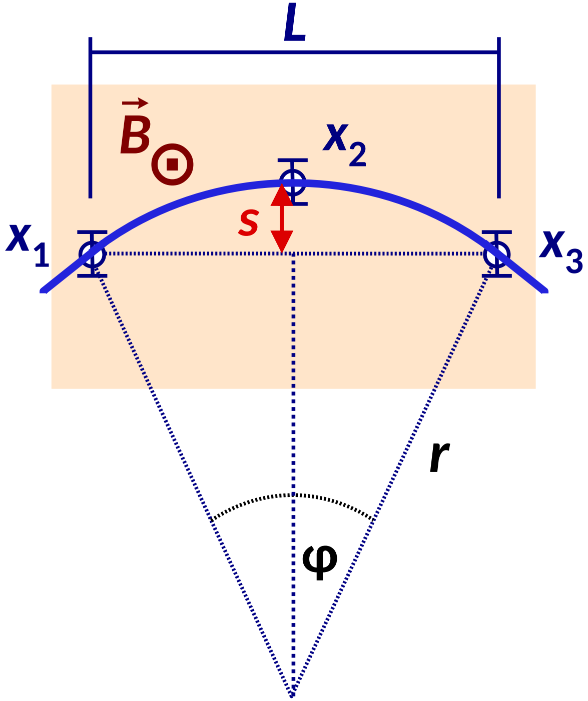
- from Lorentz force ($q = 1$):

$$r = \frac{p}{0.3\cdot B}$$

Momentum resolution

Simplified example: measure position in three points, determine bending radius from sagitta

$$\Rightarrow \quad s = \frac{0.3}{8} \cdot \frac{L^2 \cdot B}{p}$$



- measure x_1, x_2, x_3 with resolution σ_x:

$$s = x_2 - \frac{x_1 + x_3}{2} \quad \Rightarrow \quad \sigma_s^2 = \frac{3}{2}\sigma_x^2$$

$$\boxed{\frac{\sigma(p)}{p} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\,\sigma_x \cdot \frac{8\,p}{0.3\,B\,L^2}}$$

Gluckstern equation

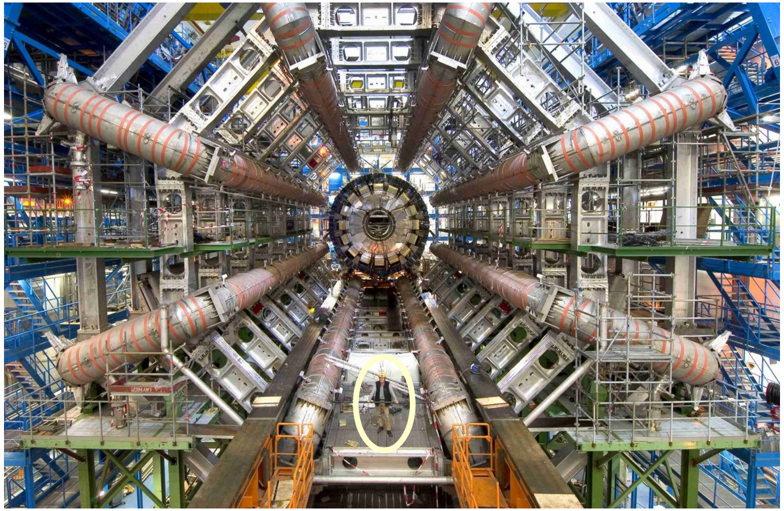
Gluckstern (1963): for *N* equidistant measurements

$$\frac{\sigma(p)}{p} \approx \sqrt{\frac{720}{N+4}} \cdot \sigma_x \cdot \frac{p}{0.3\, B\, L^2}$$

[Nucl Instr Meth 24 (1963) 381]

Relative momentum resolution

- deteriorates linearly with momentum
- improves linearly with detector resolution
- improves linearly with magnetic field
- improves <u>quadratically</u> with the length of the measured track segment



[ATLAS at LHC/CERN]

Multiple Scattering

Particle trajectory is disturbed by multiple scattering and energy loss in the material of the detector

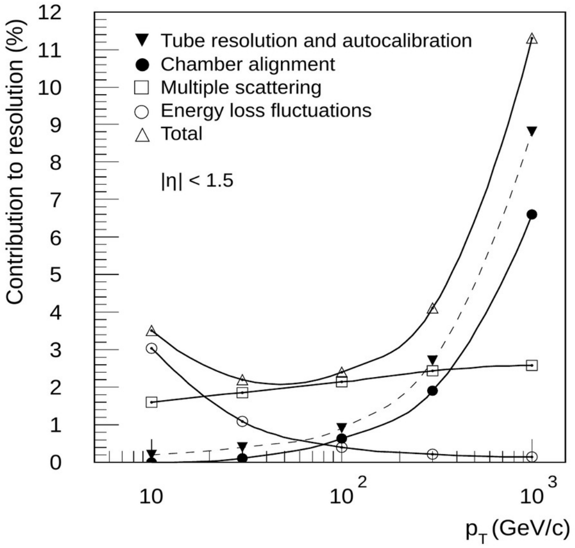
- mean scattering angle in a plane:

$$\vartheta_{rms} = \frac{13.6 \times 10^{-3}}{\beta \cdot p\,[\mathrm{GeV}]} \cdot z \cdot \sqrt{\frac{L}{X_0}} \cdot \left(1 + 0.038 \cdot \ln\left(\frac{L}{X_0}\right)\right)$$

- effect on relative momentum resolution

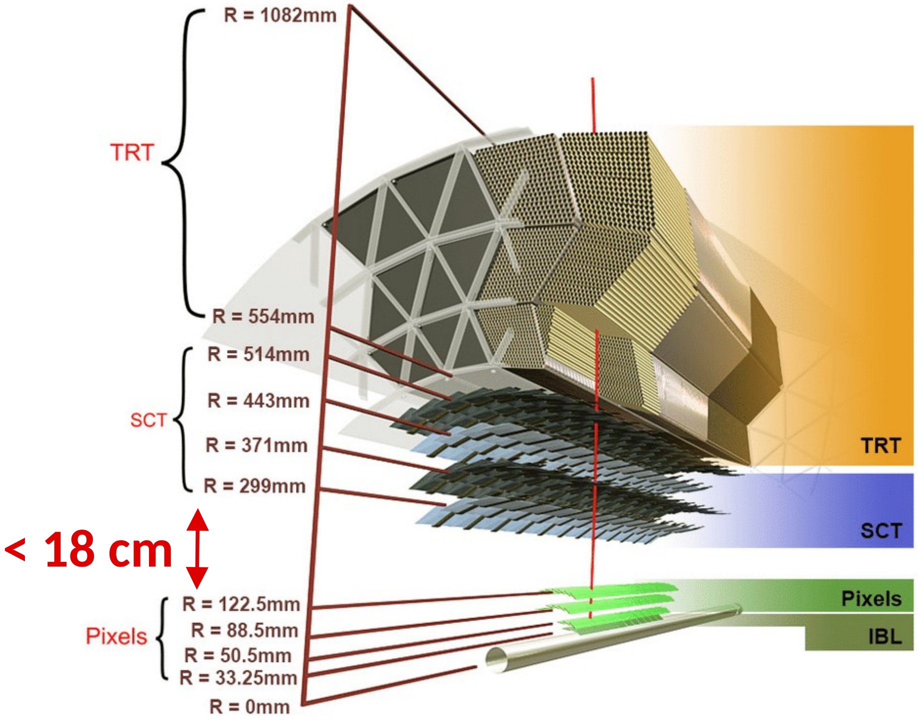
$$\frac{\sigma(p)}{p} = \frac{0.2 \cdot \sqrt{L/X_0}}{\beta \cdot B \cdot L}$$

- constant as a function of momentum for β ≈ 1
- often dominates at lower momenta



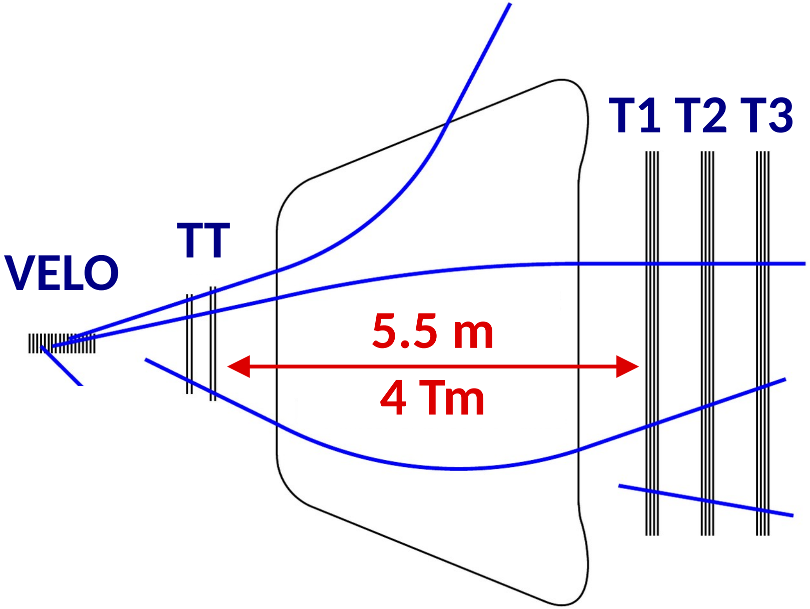
[Edda Gschwendtner, PhD thesis TU Wien (2000)]

ATLAS, CMS and LHCb



< 18 cm

ATLAS: many measurements

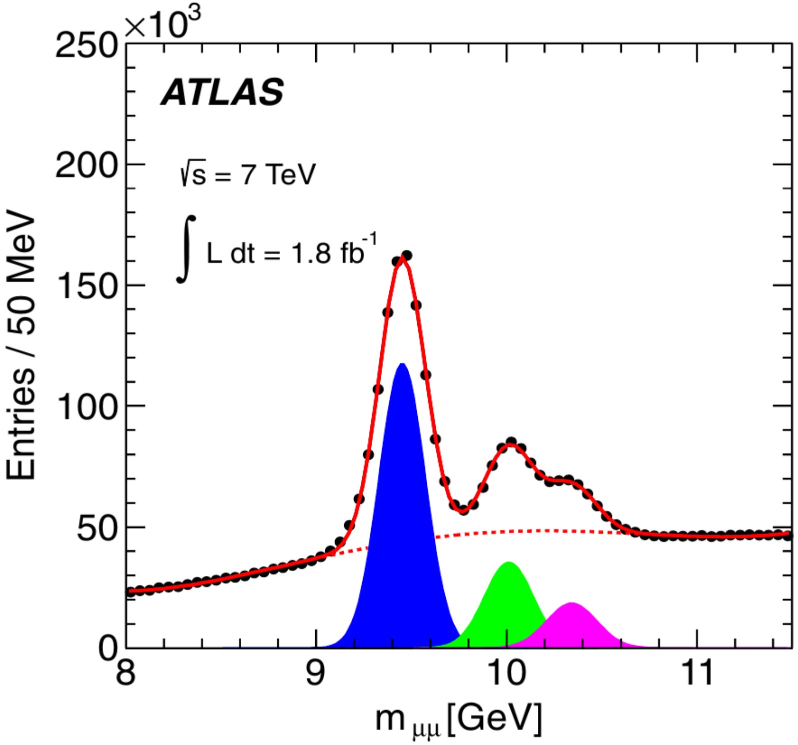


5.5 m

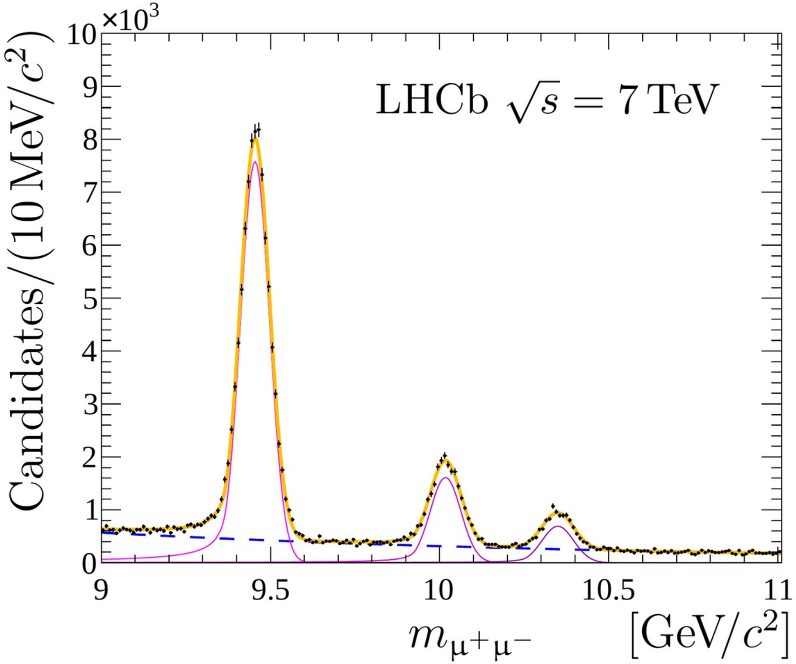
4 Tm

LHCb: little material

ATLAS, CMS and LHCb



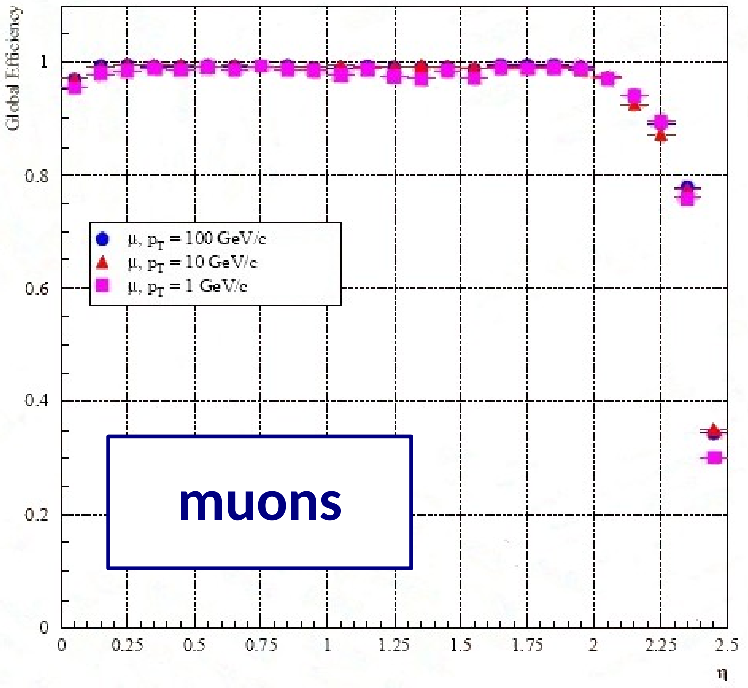
ϒ(1s), (2s), (3s) in ATLAS

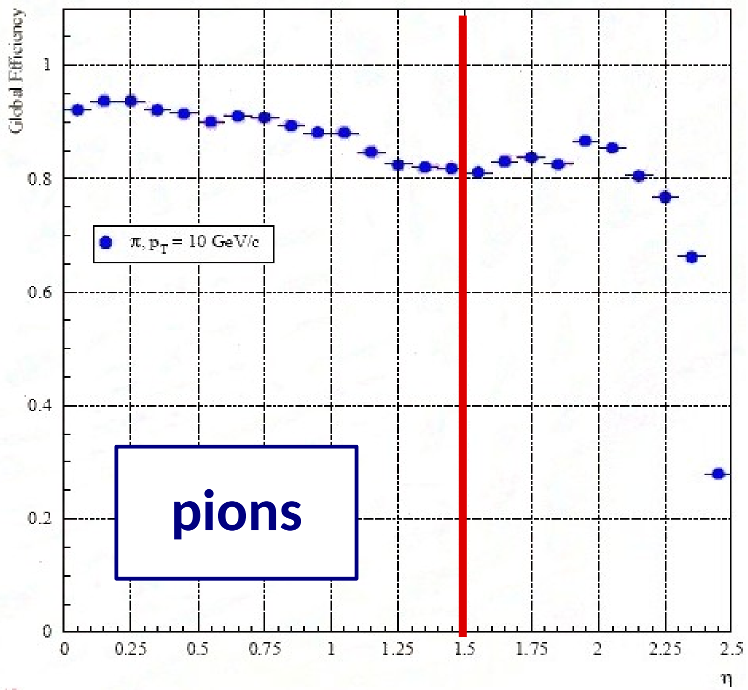


ϒ(1s), (2s), (3s) in LHCb

Hadronic Interactions

Example: track reconstruction efficiencies in CMS



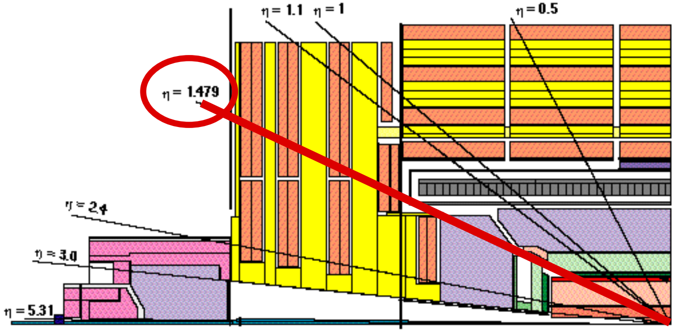


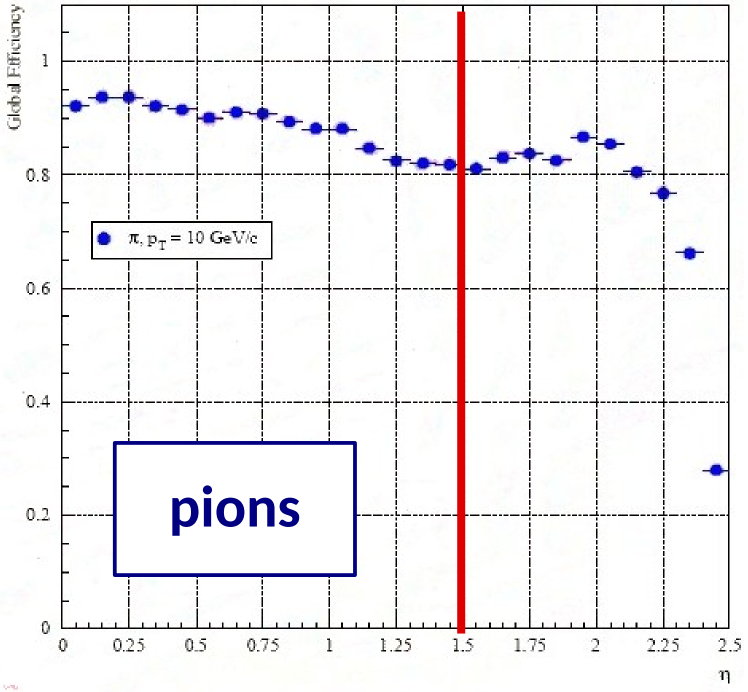
[pseudo-rapidity η ≙ polar angle of the particle]

Hadronic Interactions

Pions (and kaons, protons**) also undergo hadronic interactions in material**

- can cause large kink in the trajectory or a shower of secondary particles
- loss in reconstruction efficiency



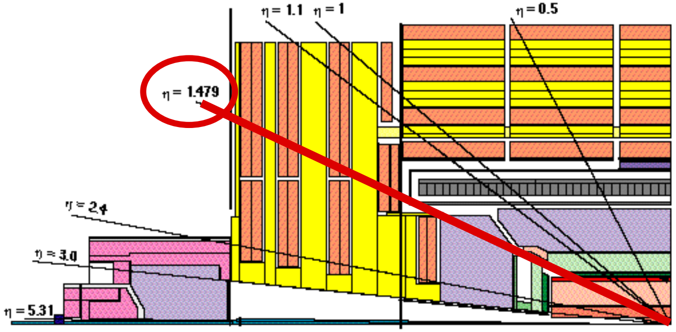


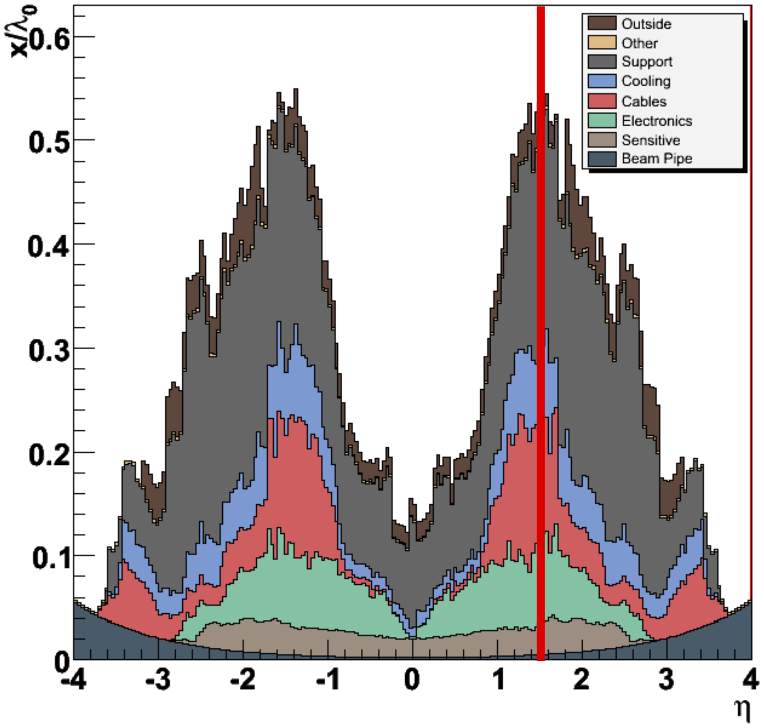
pions

Hadronic Interactions

Pions (and kaons, protons) **also undergo hadronic interactions in material**

- can cause large kink in the trajectory or a shower of secondary particles
- loss in reconstruction efficiency





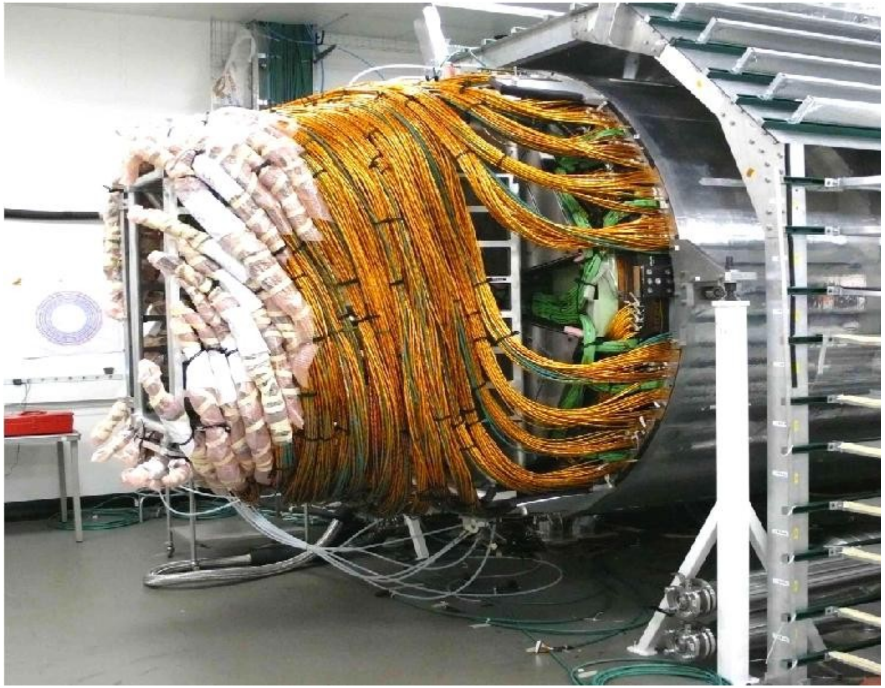
Hadronic Interactions

Pions (and kaons, protons) **also undergo hadronic interactions in material**

- can cause large kink in the trajectory or a shower of secondary particles
- loss in reconstruction efficiency

Material often dominated by cables, mechanical supports, cooling, …

- very important to find light-weight solutions (designs and materials)
- far from trivial → good engineers !!!



Quiz I

Which of these statements about relative momentum resolution are correct?

(a) it deteriorates linearly with increasing momentum of the particle

(b) it improves linearly with increasing momentum of the particle

(c) it improves linearly with improving spatial resolution of the detector

(d) it improves quadratically with the strength of the magnetic field

(e) it improves quadratically with the track length

Which of these statements about multiple scattering are correct

(a) at the LHC, multiple scattering is (almost) independent of particle momentum

(b) multiple scattering depends on the nuclear interaction length of the material

(c) the material budget of a detector is usually dominated by cables, supports, cooling

Requirements on Tracking Detectors

Spatial resolution

- precision of position measurement

Material budget

- degradation from multiple scattering etc

Granularity (cell size)

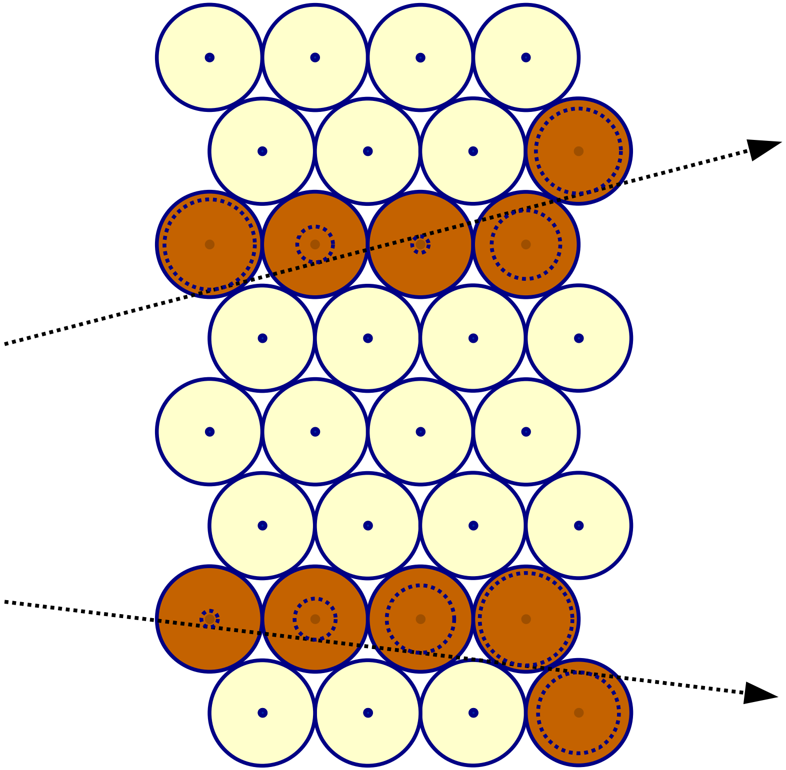
Rate capability

Robustness

- operate reliably over many years

Radiation hardness

- gradual degradation from radiation damage



Requirements on Tracking Detectors

Cost: detector must match requirements,
but should not be more expensive than needed

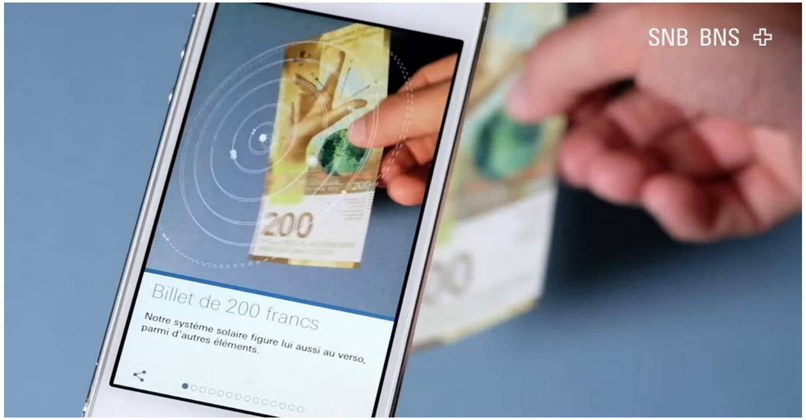
- different detector technologies to match different applications
- detector technology and readout electronics
- e.g. finer granularity (smaller cell size) → larger number of readout channels to cover the same area → higher cost

[https://www.snb.ch/en/iabout/cash/series9/id/cash_series9]

Requirements on Tracking Detectors

Cost: detector must match requirements,
but should not be more expensive than needed

- different detector technologies to match different applications
- detector technology and readout electronics
- e.g. finer granularity (smaller cell size) → larger number of readout channels to cover the same area → higher cost



Billet de 200 francs

Notre système solaire figure lui aussi au verso, parmi d'autres éléments.

[https://www.snb.ch/en/iabout/cash/series9/id/cash_series9]

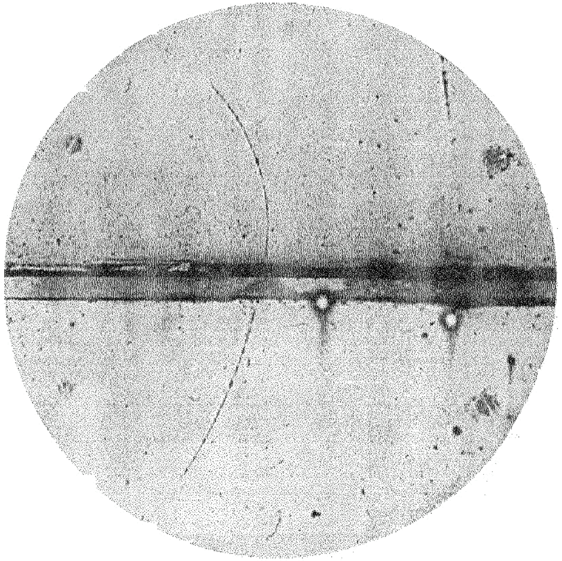
Early Tracking Detectors: Cloud Chamber

Wilson, 1911 (Nobel prize 1927**)**

- vessel filled with supersaturated water vapour
  → created by adiabatic expansion
- charged particle ionizes atoms along its trajectory
  → act as condensation nuclei → trail of droplets
- spatial resolution ≈ 100 µm
- *dE/dx* from density of droplets (→ particle id)

Operation delicate, slow and cumbersome

- expand, expose, take photograph, …



discovery of positron
(Anderson, 1932)

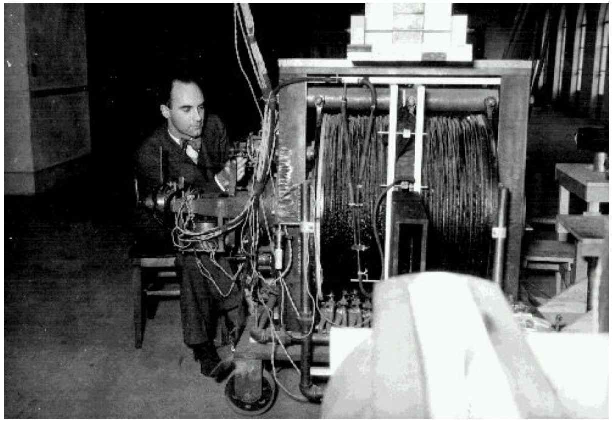
Early Tracking Detectors: Cloud Chamber

Wilson, 1911 (Nobel prize 1927)

- vessel filled with supersaturated water vapour
  → created by adiabatic expansion
- charged particle ionizes atoms along its trajectory
  → act as condensation nuclei → trail of droplets
- spatial resolution ≈ 100 µm
- *dE*/*dx* from density of droplets (→ particle id)

Operation delicate, slow and cumbersome

- expand, expose, take photograph, …



discovery of positron
(Anderson, 1932)

Early Tracking Detectors: Bubble Chamber

Glaser, 1952 (Nobel Prize 1960)

- vessel filled with superheated liquid
- charged particle deposits energy

  → trail of bubbles along trajectory
- more reliable, easier to operate

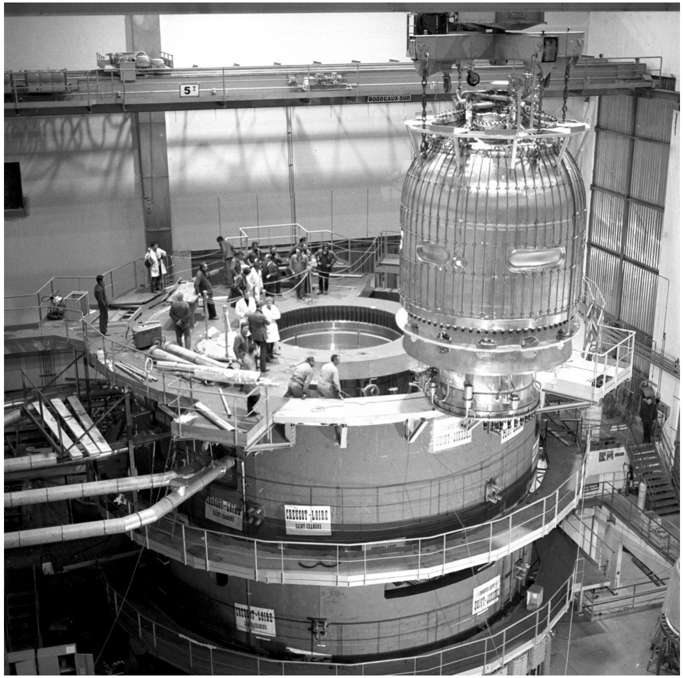
  → large detector facilities at particle beams

Example: BEBC (CERN PS and SPS, 1970 – 1984)

- 600 scientists from 50 laboratories

But still slow …

- 6.3 million photos in ≈ 15 years of operation



[http://cds.cern.ch/record/41546]

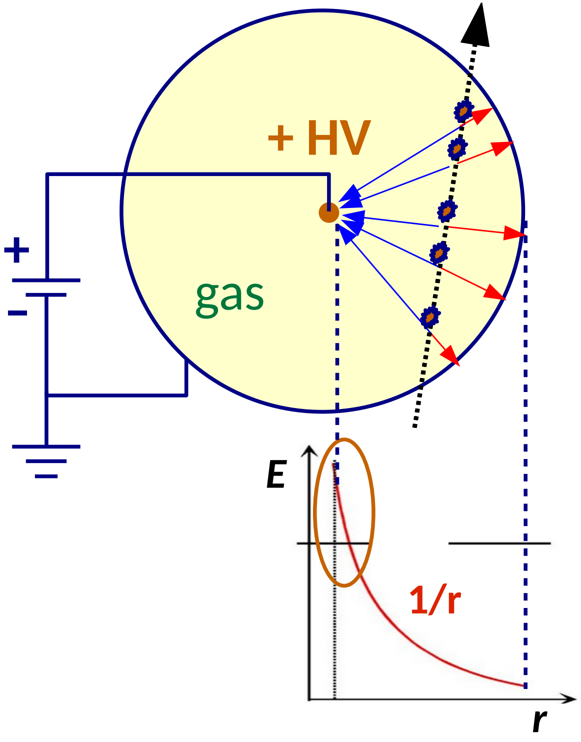
Gaseous detectors

Wire chamber: thin wire in a gas-filled volume

- high voltage between wire (+) and wall (GND)
- charged particle ionizes gas atoms
- electrons drift to wire, gain energy
- region of high field close to wire → secondary ionization → charge avalanche → voltage pulse

Drift chamber: measure the time difference between ionizing particle and signal on wire

- determine distance of particle from wire



Gaseous detectors

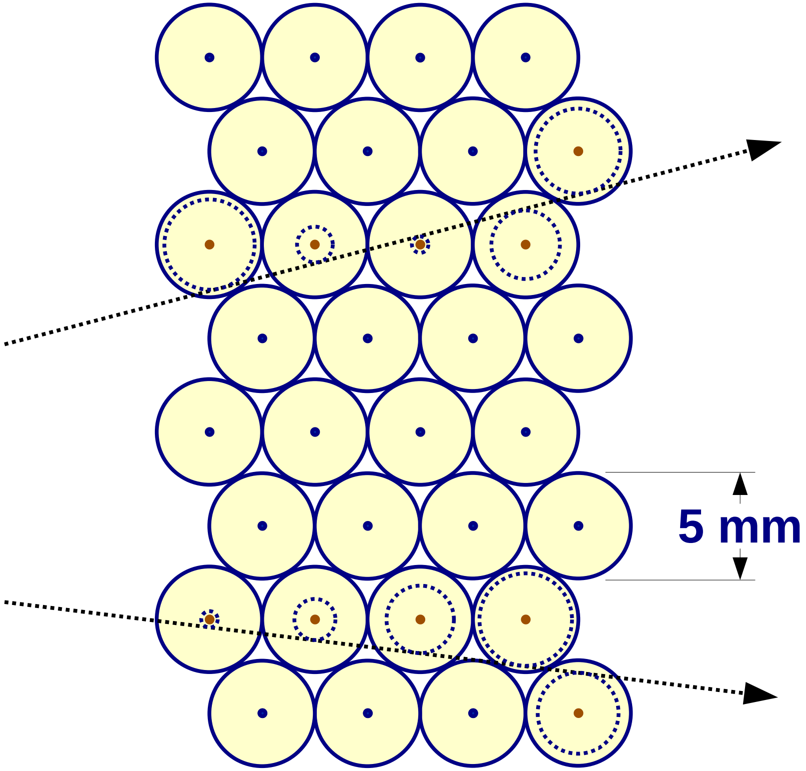
Straw drift tube detector

- layers of thin-walled, cylindrical drift cells
- employed in LHCb (2010-2018) and ATLAS

Robust, easy to cover large surfaces

- but limitations in terms of performance: granularity, spatial resolution, rate capability , radiation damage

No longer used in LHC upgrades



Silicon detectors

Segmented, reverse biased *p*–*n* junction

- typical bulk thickness 300–500 µm
- typical implant pitch 50–200 µm

Apply reverse bias voltage

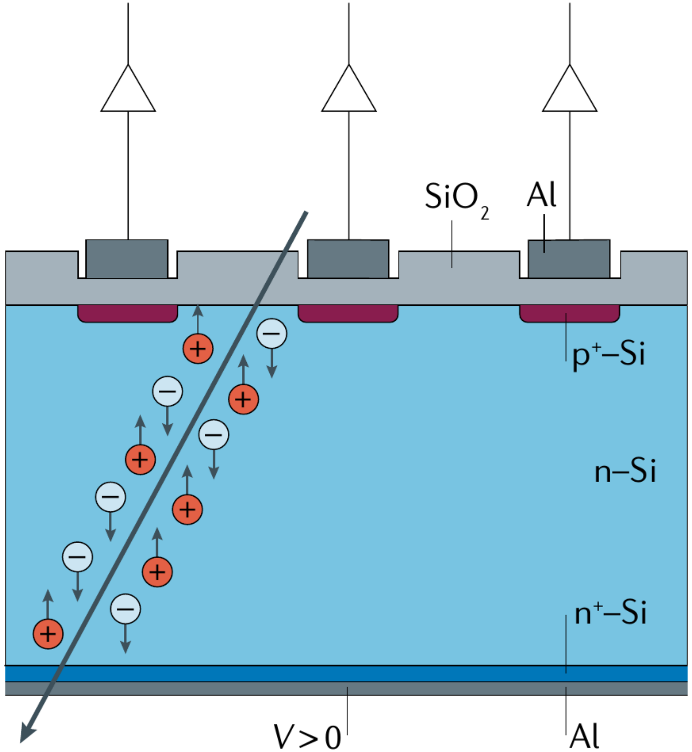
- deplete bulk → electric field

Ionizing particle creates *e*/*h* pairs

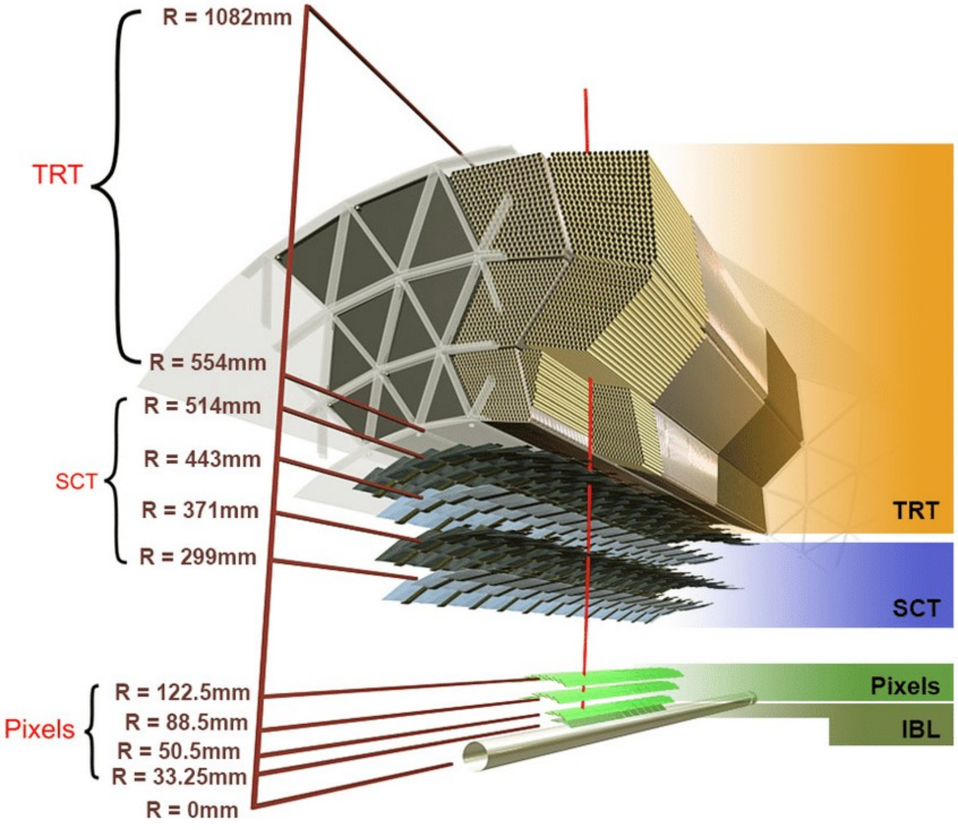
- drift to implants, induce signal

Better granularity, resolution, rate capability, radiation hardness than gaseous detectors

- but a lot more expensive



Example: ATLAS tracking system



TRT: straw drift tubes

- 350’000 readout channels

SCT: silicon strip detectors

- 60 m^2 active area
- 6’000’000 readout channels

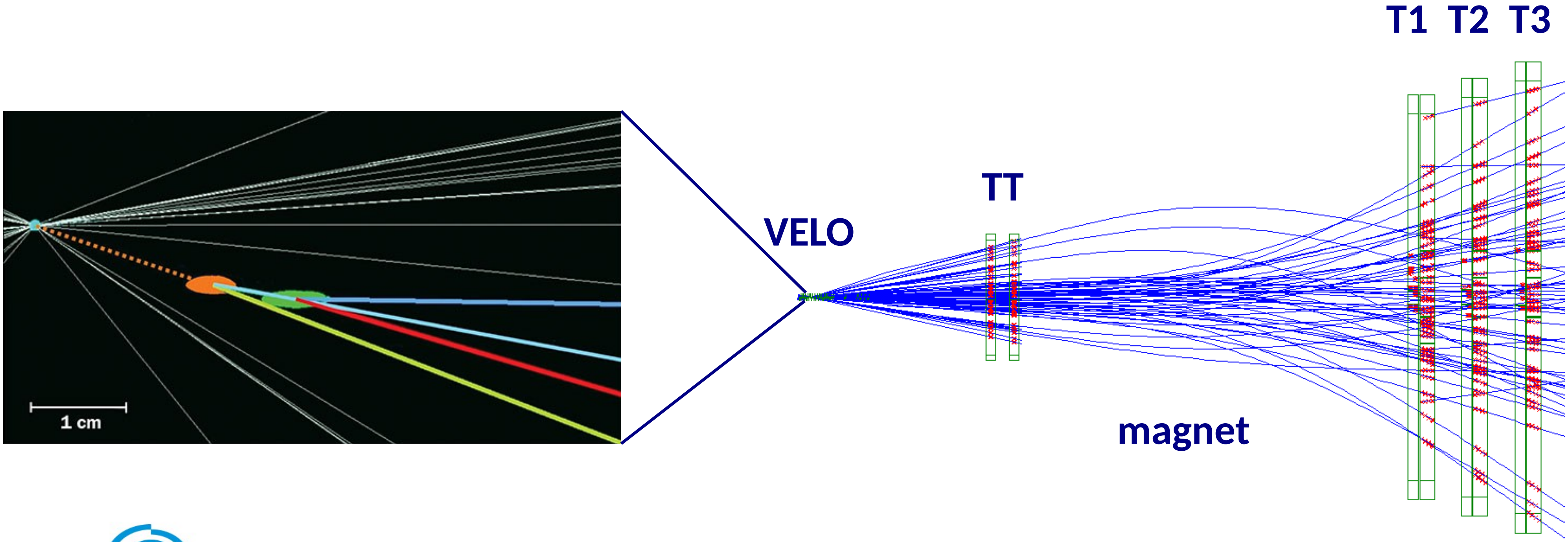
Pixels: silicon pixel detector

- 50 µm × 400 µm
- 1.8 m^2 active area
- 80’000’000 readout channels

Example: LHCb tracking system

VELO: reconstruction of primary and secondary vertices

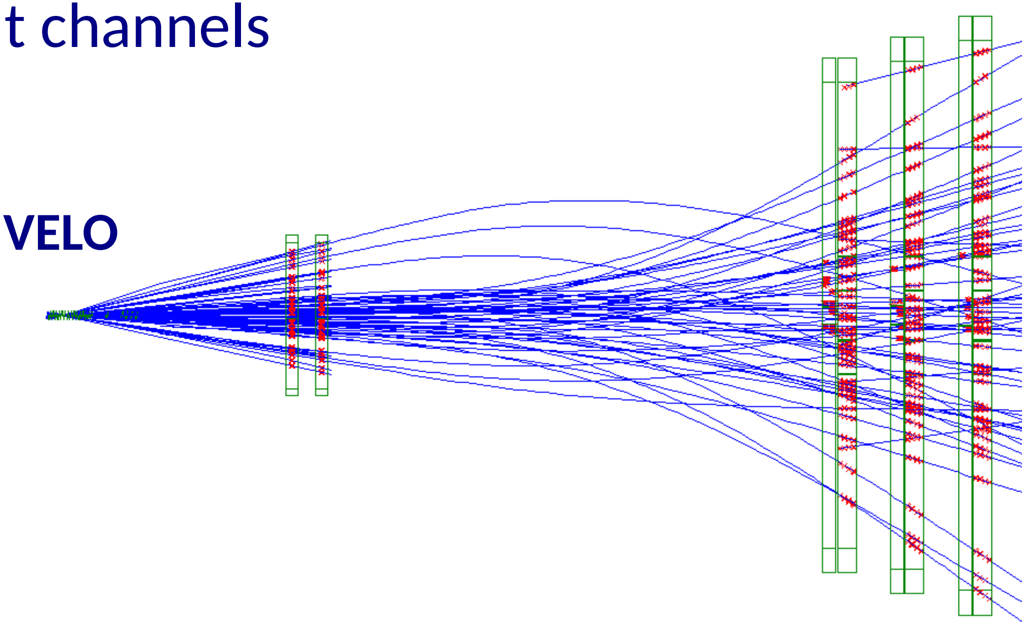
TT, T1–T3: momentum measurement



Example: LHCb tracking system

VELO: small, close to interaction point, high particle density

- silicon strips with fine granularity (40–100 µm pitch, 3.8–33.8 mm long)
  - spatial resolution ≈ 4–40 µm for vertex reconstruction
- active area ≈ 0.22 m², 172’000 readout channels

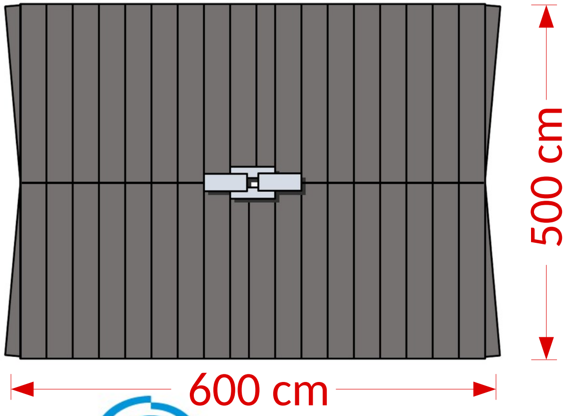


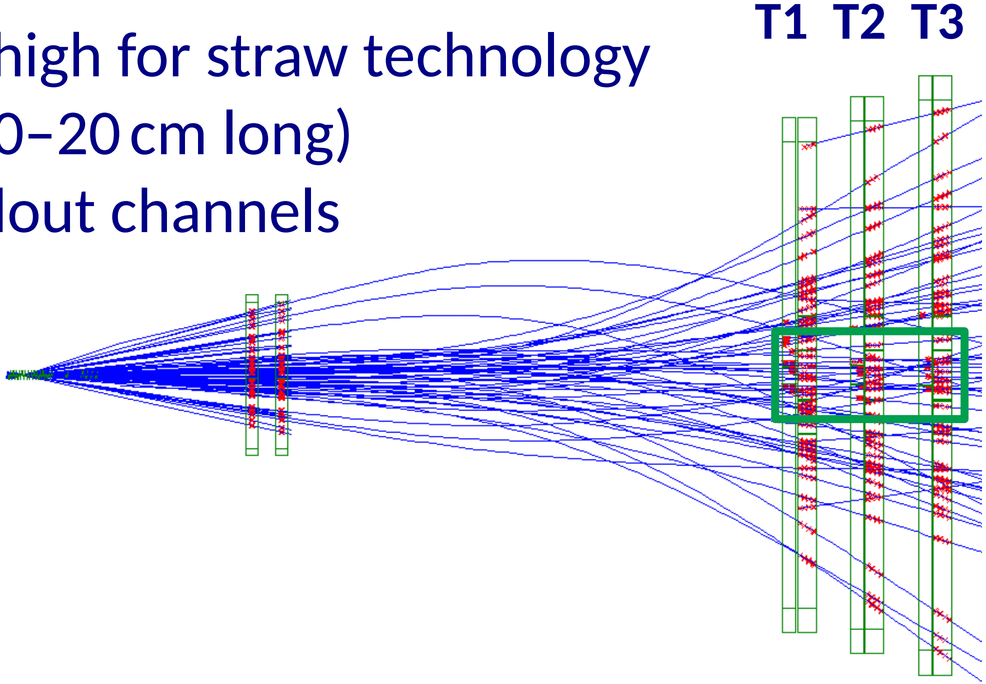
[http://cds.cern.ch/record/1024838]

Example: LHCb tracking system

T1–T3: large surface (active area ≈ 350 m^2)

- straw drifttubes (5 mm diameter, 2.5 m long)
  - spatial resolution ≈ 100 µm for momentum measurement
- innermost region: particle density too high for straw technology
  ≈ 4 m^2 of silicon strips (200 µm pitch, 10–20 cm long)
- 54’000 (straws) + 130’000 (silicon) readout channels

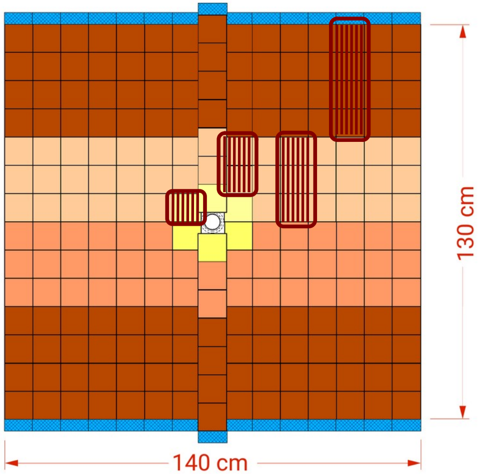


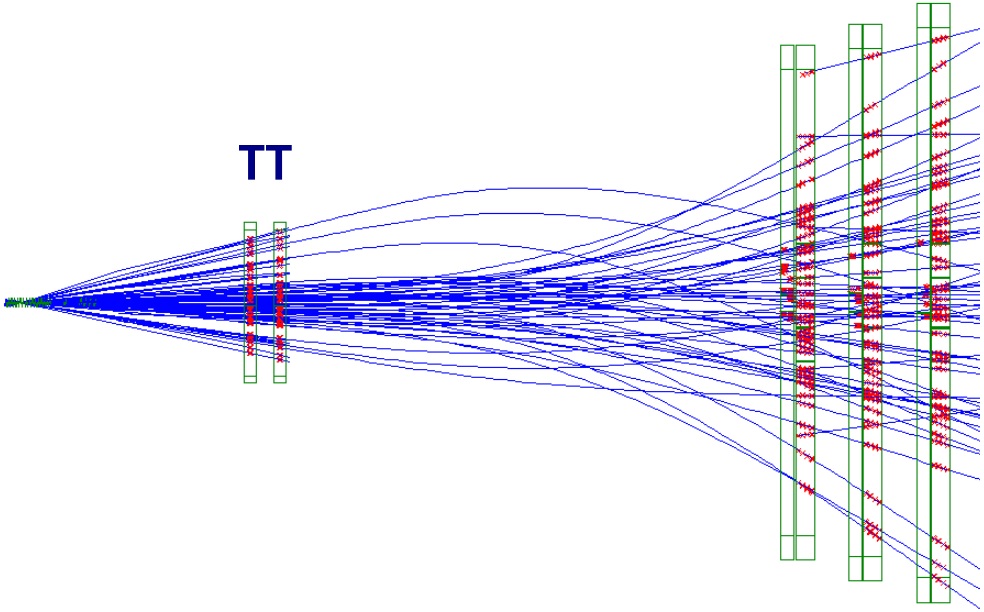


Example: LHCb tracking system

TT: in between (active area ≈ 8 m²)

- silicon micro-strips (190 µm pitch, 10–40 cm long)
  - shorter strips (finer granularity) in inner region
  - spatial resolution ≈ 60 µm
- 143’000 readout channels





[https://lhcb.physik.uzh.ch/ST/public/photos]

Quiz II

What determines the necessary granularity of a detector?

(a) the density of charged particles crossing the detector
(b) the desired spatial resolution
(c) the rate at which charged particles cross the detector

Why is a spatial resolution of 100 µm sufficient for T1–T3 in LHCb?

(a) the particle density is low enough
(b) LHCb does not need better momentum resolution
(c) the momentum resolution is anyway limited by multiple scattering

Why do we employ longer silicon strips in the outer regions of the TT?

(a) to reduce the material budget
(b) to save money

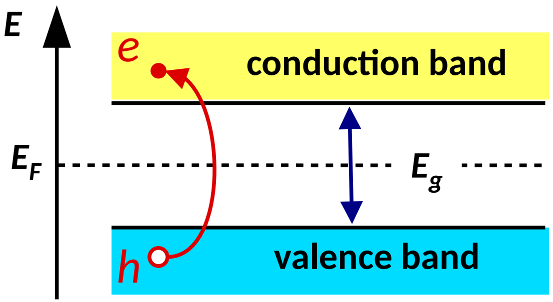
Silicon as detector material

Monocrystalline silicon:

- bandgap energy 1.12 eV

For an ionizing particle:

- average 3.6 eV to excite an *e*/*h* pair



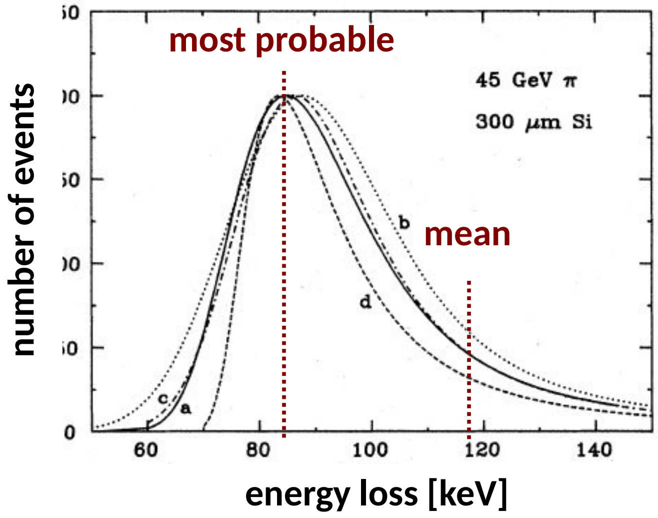
Energy loss in a thin layer: Ландау distribution

- mip$^{(*)}$ in silicon: mean $dE/dx \approx 3.9\,\mathrm{MeV/cm}$

  → 32’500 *e*/*h* pairs in 300 µm of silicon

- more important: most probable signal

  → 22’500 *e*/*h* pairs in 300 µm of silicon



$^{(*)}$mip = minimum ionizing particle

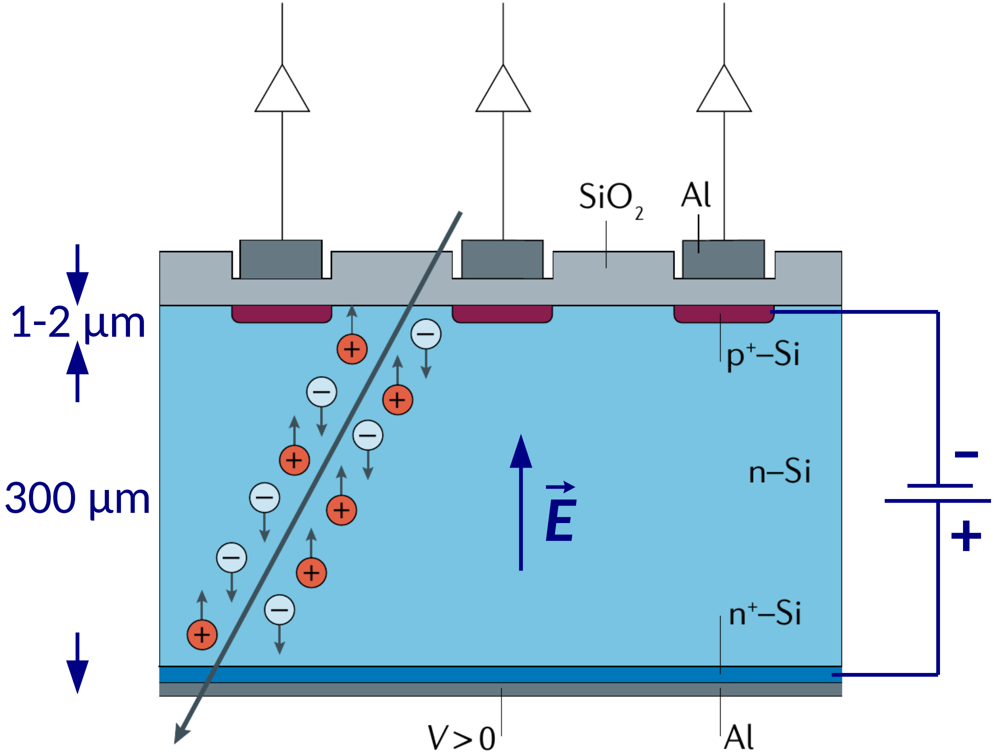
Silicon detectors

Electric field to collect *e* and *h* created by an ionizing particle:

- reverse-biased *p*-*n* junction, e.g. *p*-doped implants in *n*-doped bulk

Segmented implants to obtain position information

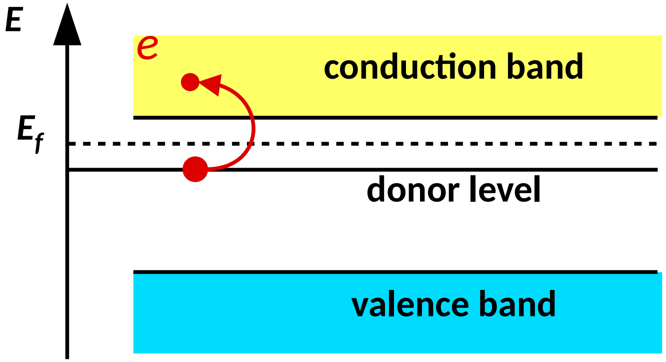
- strips or pixels
- granularity and spatial resolution determined by size of pixels or pitch and length of strips

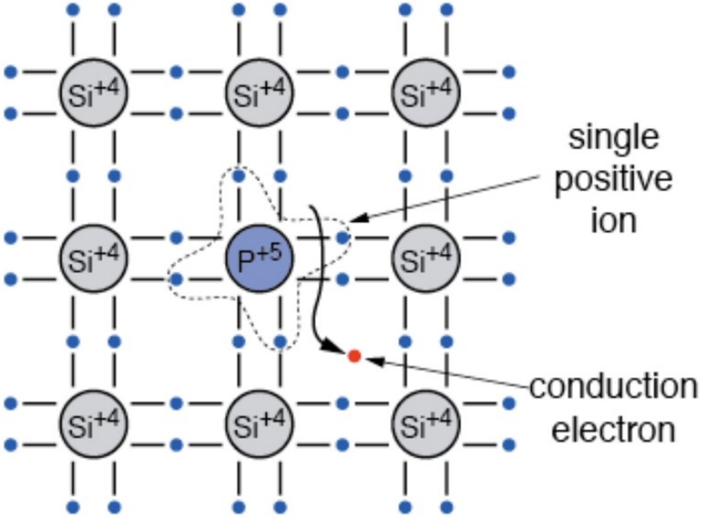


n-doped silicon

Introduce "donor" atoms (5 valence *e*⁻, e.g. P) into Si lattice

- excess electrons at energy levels just below conduction band
- loosely bound → can move through lattice



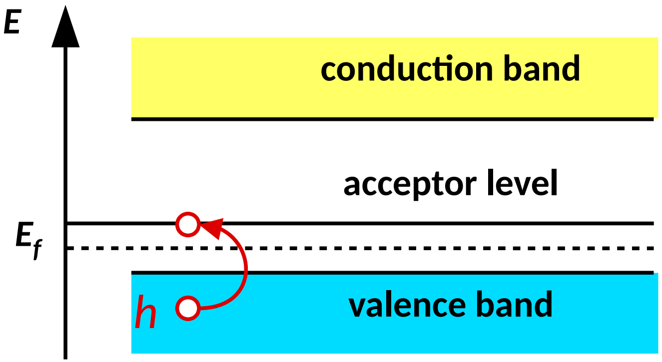


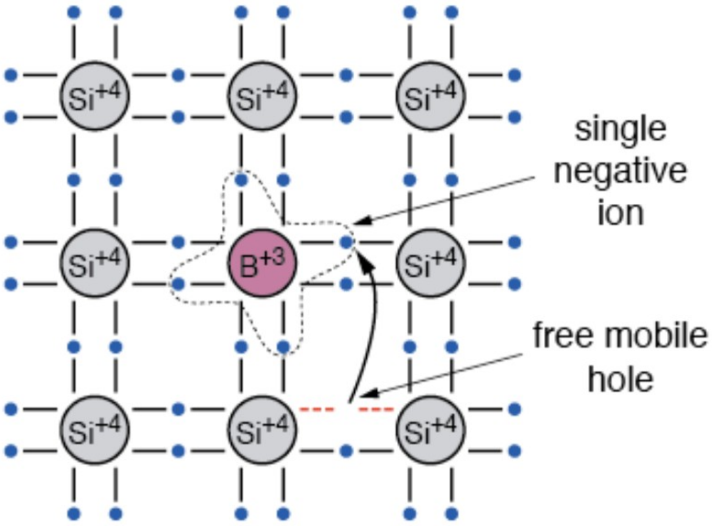
- electrons are "majority" charge carriers

p-doped silicon

Introduce "acceptor" atoms (3 valence *e*⁻, e.g. B)

- energy levels just above valence band
- loosely bound holes → can move through lattice





- holes are "majority" charge carriers

p–*n* junction

Density gradient of majority charge carriers across junction

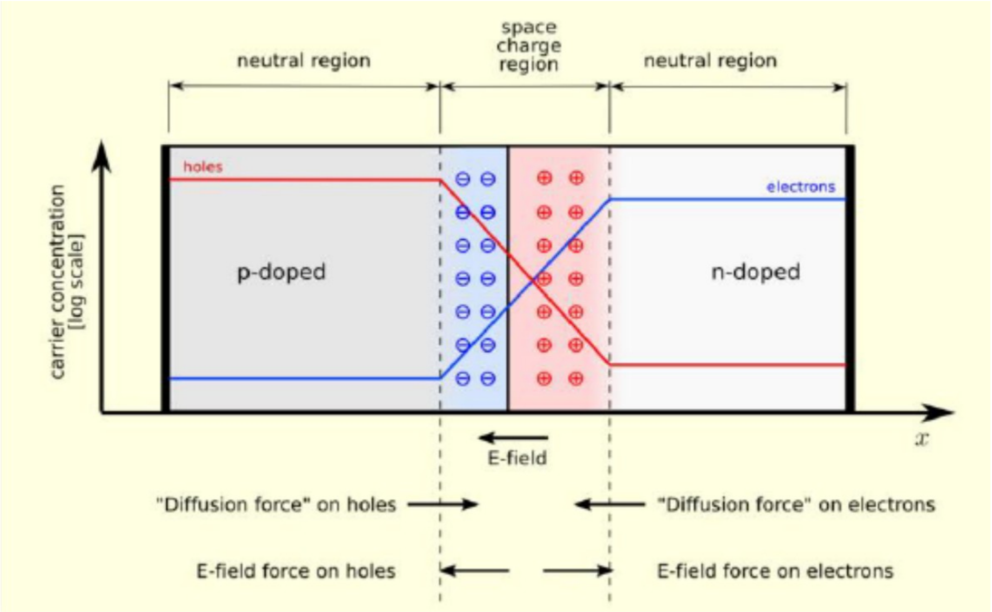
- diffusion of *h* from *p*-side to *n*-side
- diffusion of *e* from *n*-side to *p*-side

Recombination → depletion zone

- *p*-side: *e* with acceptor atoms
- *n*-side: *h* with donor atoms

Movement of charge → electric field

- steady state: equilibrium between diffusion and Coulomb force



[https://indico.cern.ch/event/190055/]

p–*n* junction

Intrinsic bias voltage:

$$-\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon} \quad ; \quad \rho(x) = e\cdot\left(N_d(x) - N_a(x)\right)$$

$$\Rightarrow \quad \Delta V_i = \frac{e}{2\varepsilon}\cdot\left(N_d\, d_n^2 + N_a\, d_p^2\right)$$

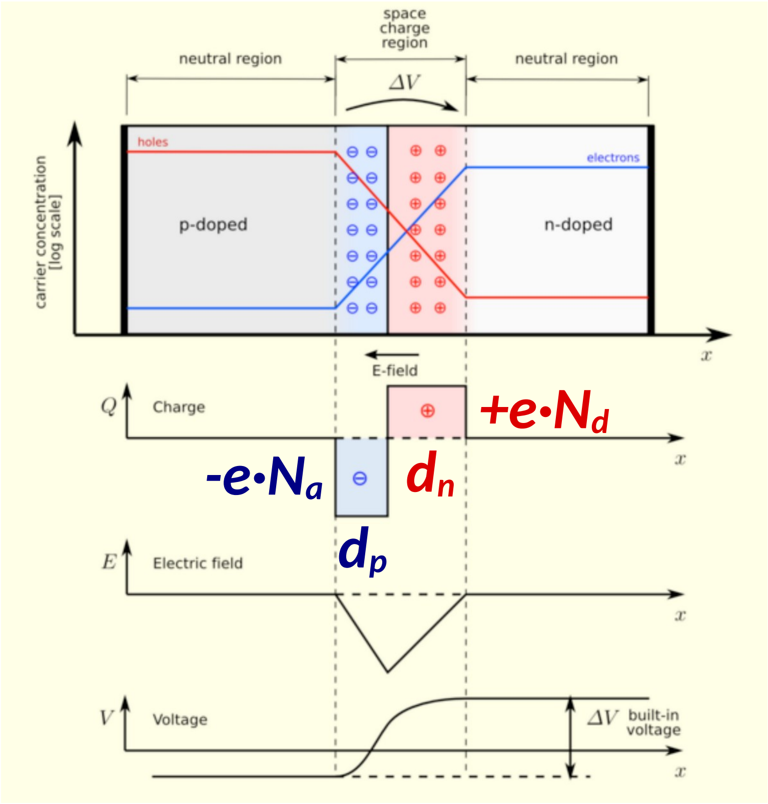
Charge conservation:

$$N_a\, d_p = N_d\, d_n$$

p-in-*n* detector: want to deplete *n*-type bulk

$$N_a \gg N_d \quad \Rightarrow \quad d_n \gg d_p$$

$$\Rightarrow \quad d_n = \sqrt{\frac{2\varepsilon\cdot\Delta V_i}{e\cdot N_d}}$$



[https://indico.cern.ch/event/190055/]

Reverse biased junction

Example: $N_d = 1.4 \times 10^{12} / \mathrm{cm}^3$

$$\Delta V_\mathrm{i} \approx 0.65\ \mathrm{V} \quad ; \quad d_n \approx 25\ \mu\mathrm{m}$$

Apply external voltage to increase the thickness of depletion zone

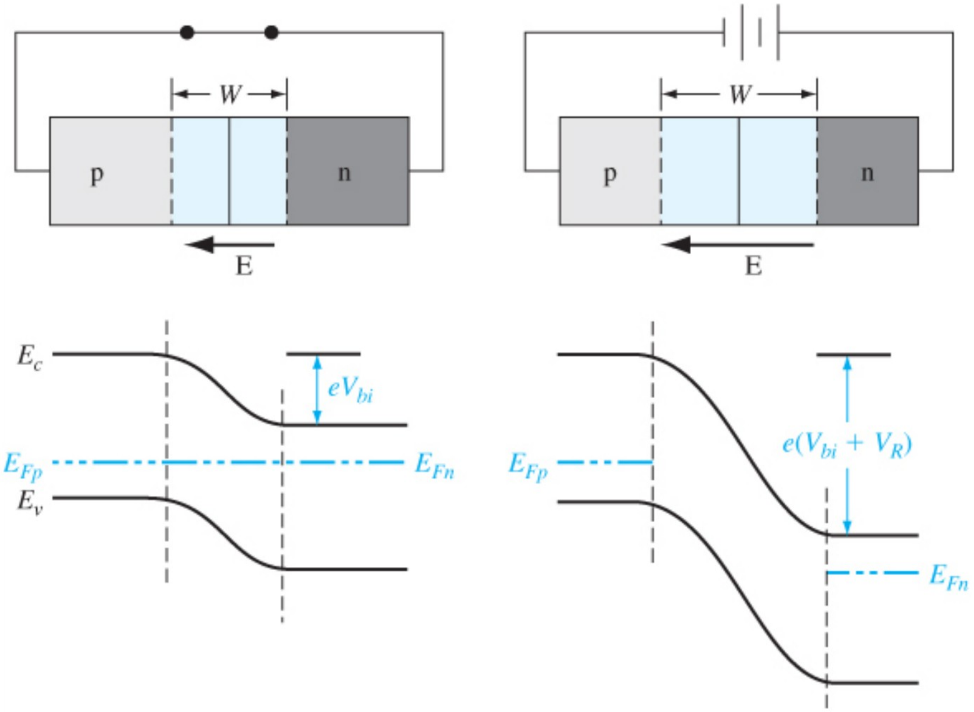
$$d_n = \sqrt{\frac{2\varepsilon \cdot \left(\Delta V_\mathrm{i} + V_\mathrm{b}\right)}{e \cdot N_d}}$$

To fully deplete bulk of thickness *D* :

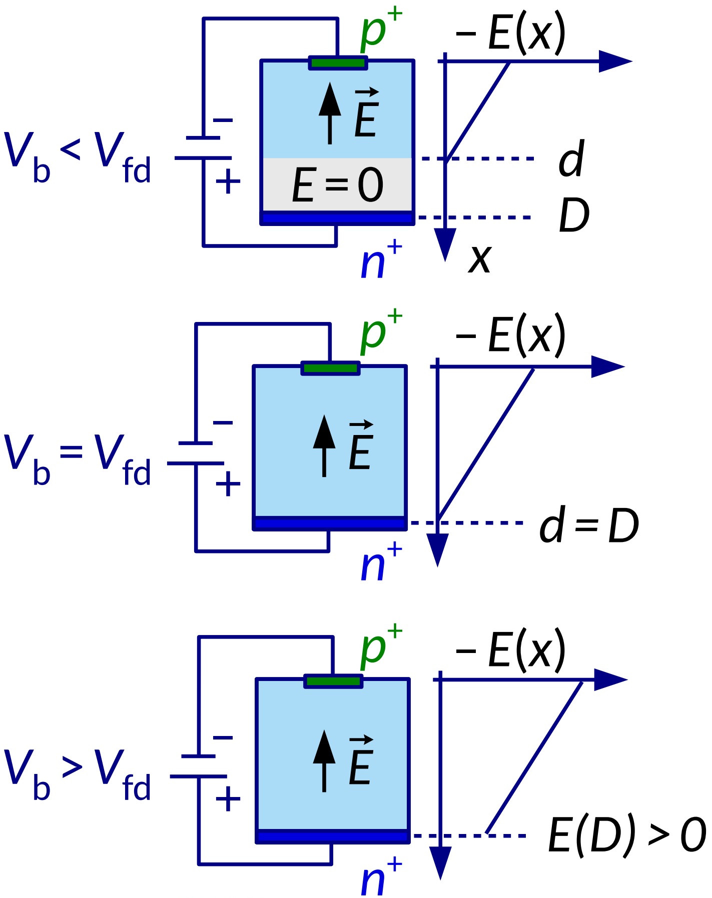
$$V_\mathrm{fd} = \frac{e}{2\varepsilon} \cdot N_D \cdot D^2$$

Example: $N_D = 5 \times 10^{12} / \mathrm{cm}^3$, $D = 300\ \mu\mathrm{m}$

$$V_\mathrm{fd} = 100\ \mathrm{V}$$



Full depletion and over-depletion



p–*n* Junction

- depletion zone, electric field
- intrinsic thickness ≈ 25 µm

Reverse bias voltage

- increase thickness of depletion zone

Full depletion

- depletion zone extends to backplane
- but $E = 0$ at backplane

Overdepletion

- increase E → faster charge collection
  → faster signal

Signal duration

Signal on implants induced by drifting charge carriers

- drift velocity proportional to electric field: $v(x) = \mu \cdot E(x)$

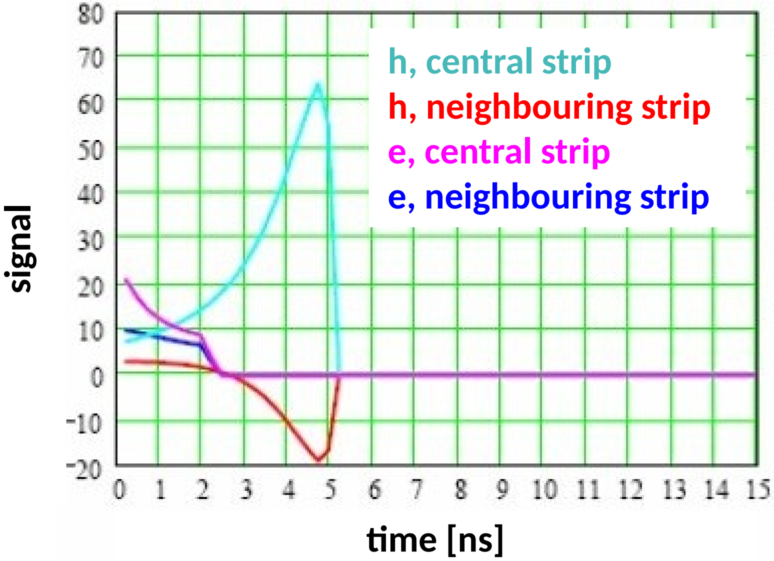
$$\left.\begin{array}{l} \mu \approx 1500\,\mathrm{cm^2/Vs} \text{ for } e \\ \mu \approx \;\; 450\,\mathrm{cm^2/Vs} \text{ for } h \end{array}\right\} \text{charge carrier “mobility”}$$

- maximum drift time for $V_b \gg V_{fd}$:

$$t_{max} \propto \frac{D^2}{2\mu \cdot V_b}$$

$$\left.\begin{array}{l} D = 300\,\mu\mathrm{m} \\ V_b = 200\,\mathrm{V} \end{array}\right\} \begin{array}{l} t_{max} = 3.5\,\mathrm{ns} \text{ for } e \\ t_{max} = 11\,\mathrm{ns} \text{ for } h \end{array}$$

p-in-*n* detector



Signal-to-Noise

Need to cut on signal amplitude to separate between

- signals from ionizing particles
- noise signals from detector, electronics

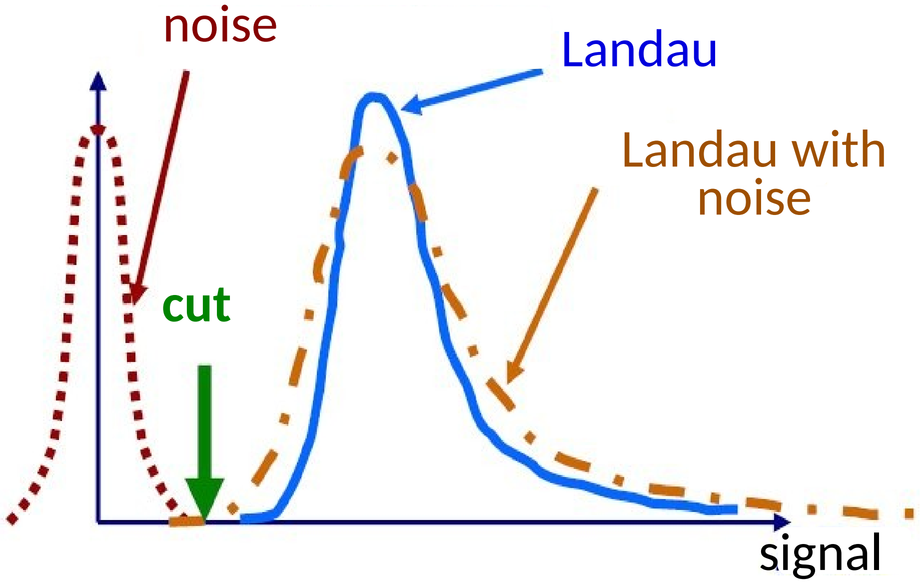
Figure of merit (by convention)**:**

$$S/N \equiv \frac{\text{most probable signal for mip}^{(*)}}{\text{rms of noise}}$$

(rule of thumb: need $S/N > 10$)

***S* determined by detector thickness**

smaller N ↔ thinner detectors



[https://indico.cern.ch/event/190055/]

(*) minimum ionizing particle

Noise sources

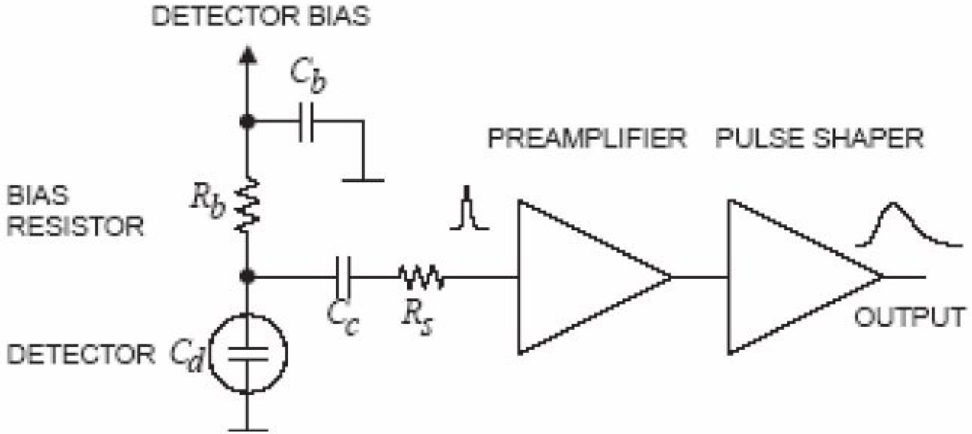
Statistical fluctuations in detector leakage currents

- suppress leakage current by operating at low temperature

Current fluctuations in resistors

- make serial resistance small

Charge fluctuations at the input transistor of the preamplifier



Noise sources

Statistical fluctuations in detector leakage currents

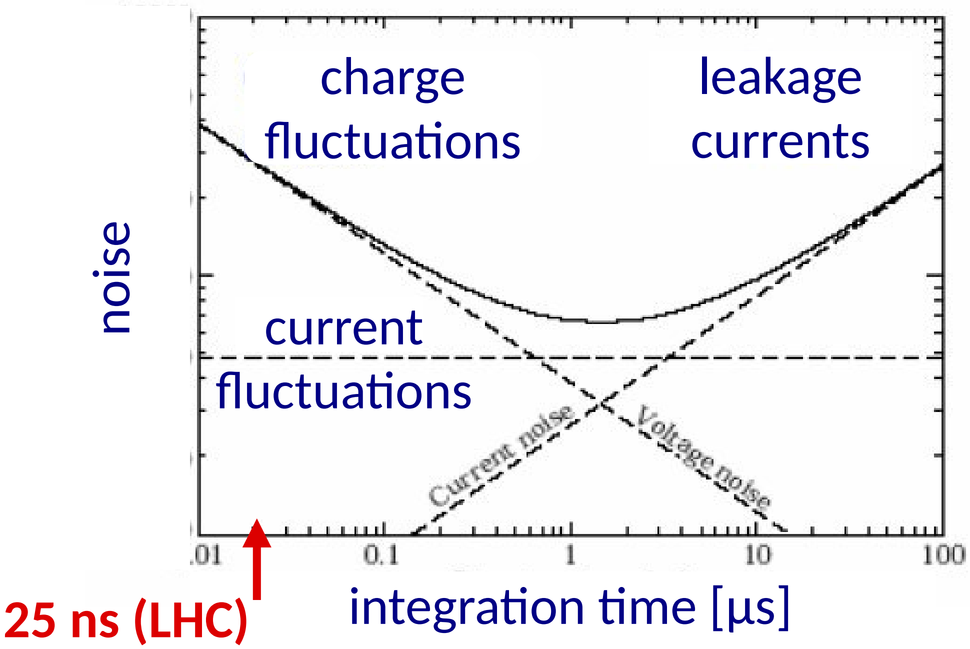
- suppress leakage current by operating at low temperature

Current fluctuations in resistors

- make serial resistance small

Charge fluctuations at the input transistor of the preamplifier

- dominates for short integration time
- proportional to detector capacitance (smaller cell size → less noise)



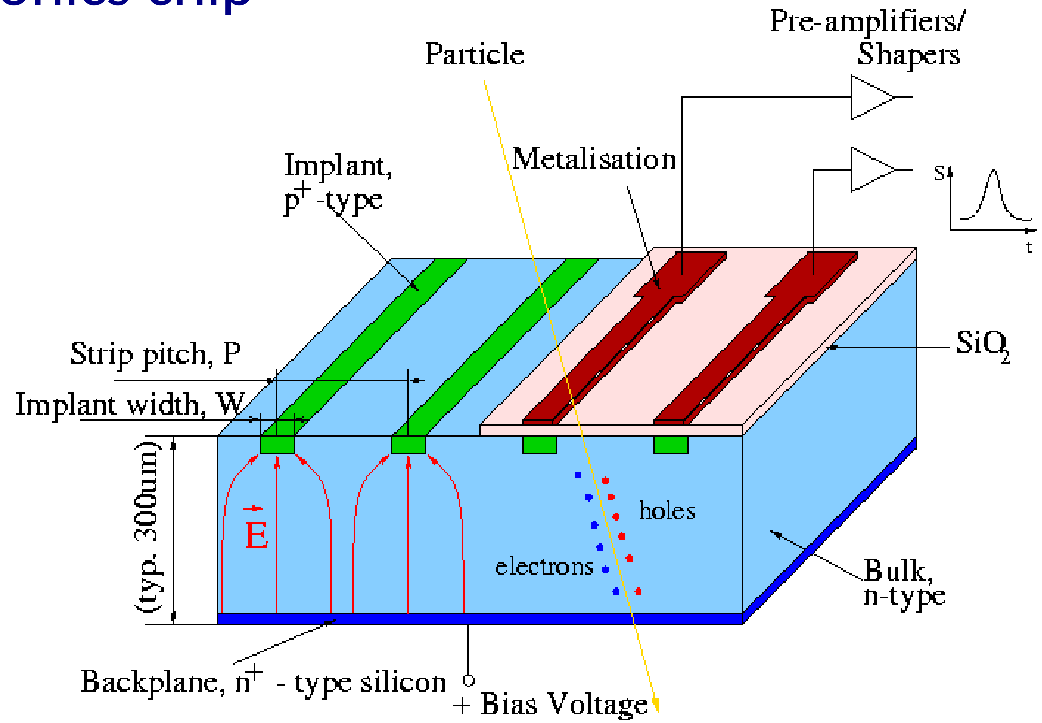
Strip detector

Read out all strips at one edge of the sensor

- wire bonds to the input of an electronics chip
- metalisation (Al) on top of implants to minimize serial resistance

Usually AC coupled readout

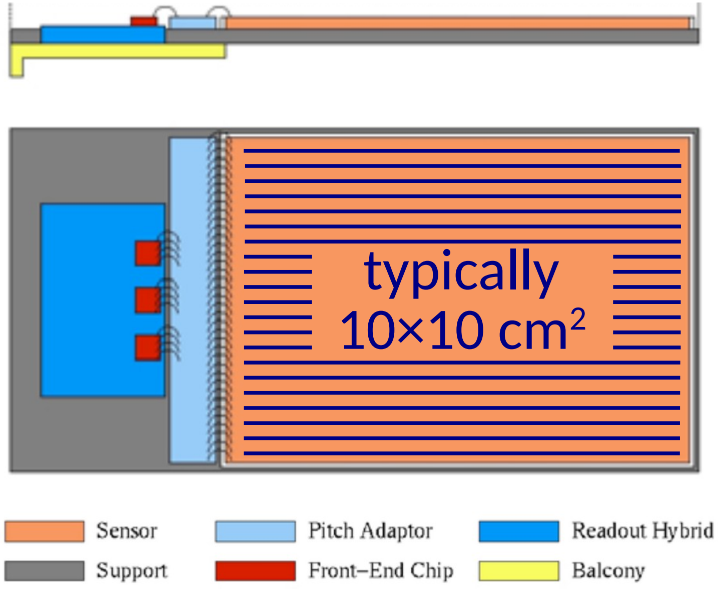
- thin, insulating layer (SiO_2) between implant and metal strip
- protect pre-amplifier from detector leakage current



Detector module

Silicon sensor + pitch adaptor + readout “hybrid” + support

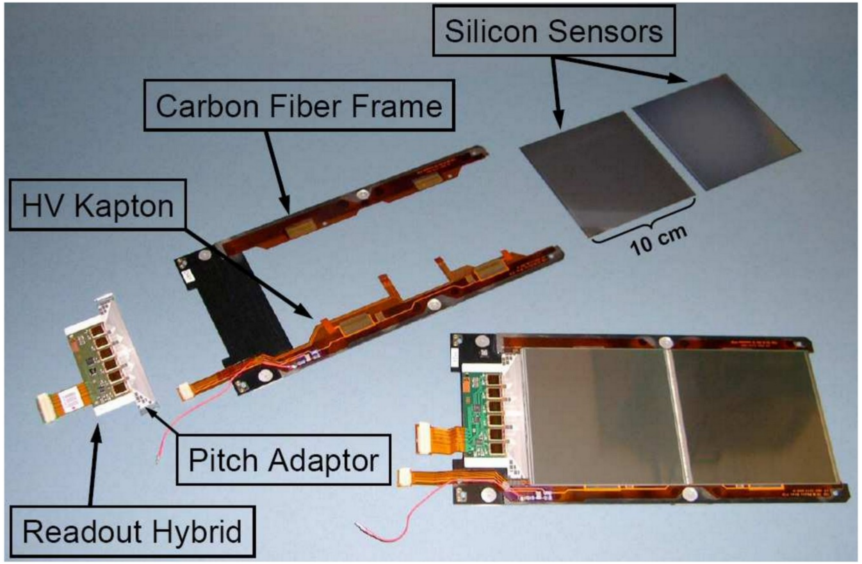
- readout hybrid carries front-end chips ;
  connectors for signals, low voltage, bias voltage ;
  capacitors and resistors for voltage filtering
- front-end chips usually integrate amplifiers, comparators or analog-to-digital converters, digital logic for data processing and formating, output line drivers for signal transmission
- one chip typically has 128 input channels
- 10 cm wide sensor with ≈ 200 µm pitch
  → 512 strips → 4 front-end chips


typically $10\times10\ \mathrm{cm}^2$

Detector module

Minimize amount of “dead” material

- pitch adaptors: usually aluminium traces on a thin (≈ 200 µm) glass or ceramic substrate
- readout hybrid: usually copper traces on thin (≈ 80 µm) polyimide film (Kapton)
- supports: usually carbon-fibre
- connectors and cables to transport signals and supply voltages to the outside
- cooling for electronics and sensors

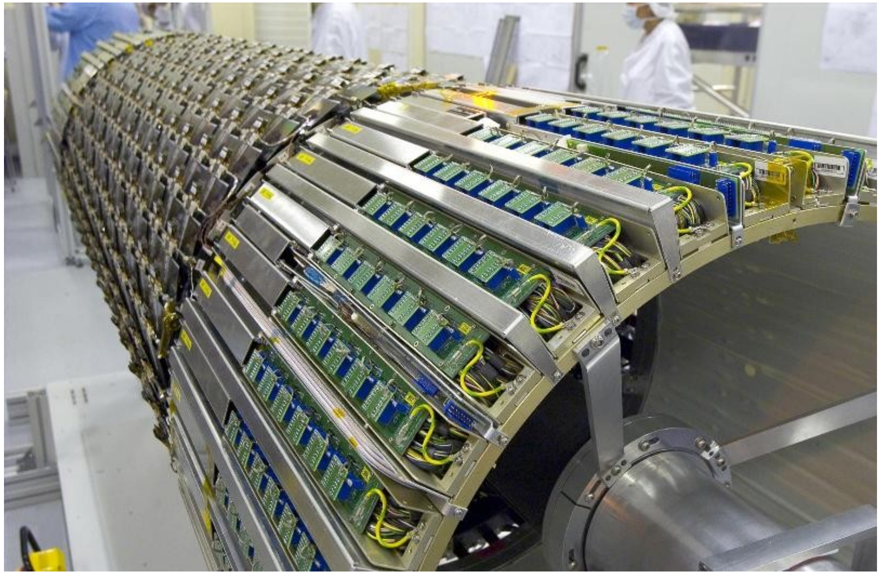


[https://www.etp.kit.edu/~hartmann/silicontracking.pdf]

Detector system

Detector = array of many modules

- light-weight support structures that
  → allow to position modules to ≈ 100 µm precision over distances of several meters
  → are stable over several years (vibrations, temperature & humidity variations, radiation damage, fire hazards …)
- supports and services (cables and cooling) usually dominate material of the detector
  → interesting challenges for engineers

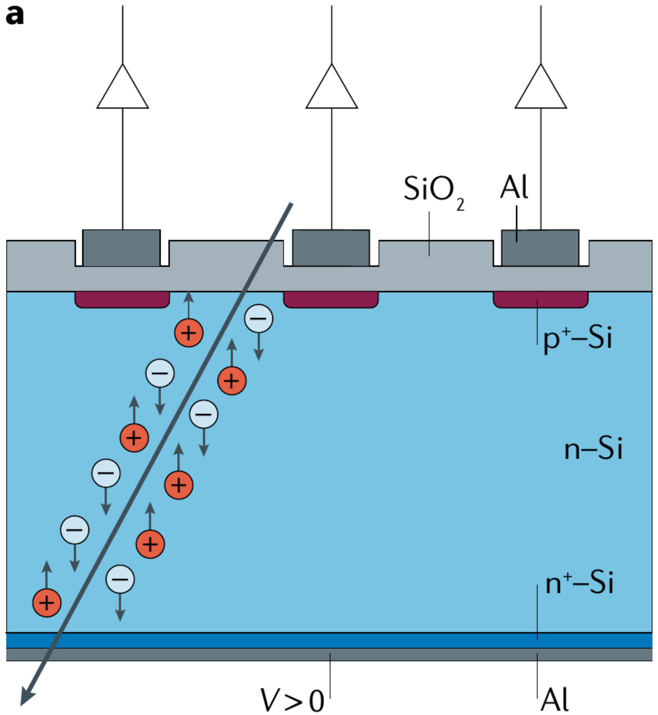


Silicon tracker of the
CMS experiment at LHC/CERN

Pixel detector

Implants segmented in pixels (typical size 100 × 150 μm)

- finer granularity for higher particle density
- measure 2 coordinates
  → easier for track reconstruction
- smaller cells → smaller capacitance
  → less noise → thinner sensor
- but: large number of read-out channels
  → e.g. CMS pixel vertex detector:
  124 million channels to cover 1.24 m^2

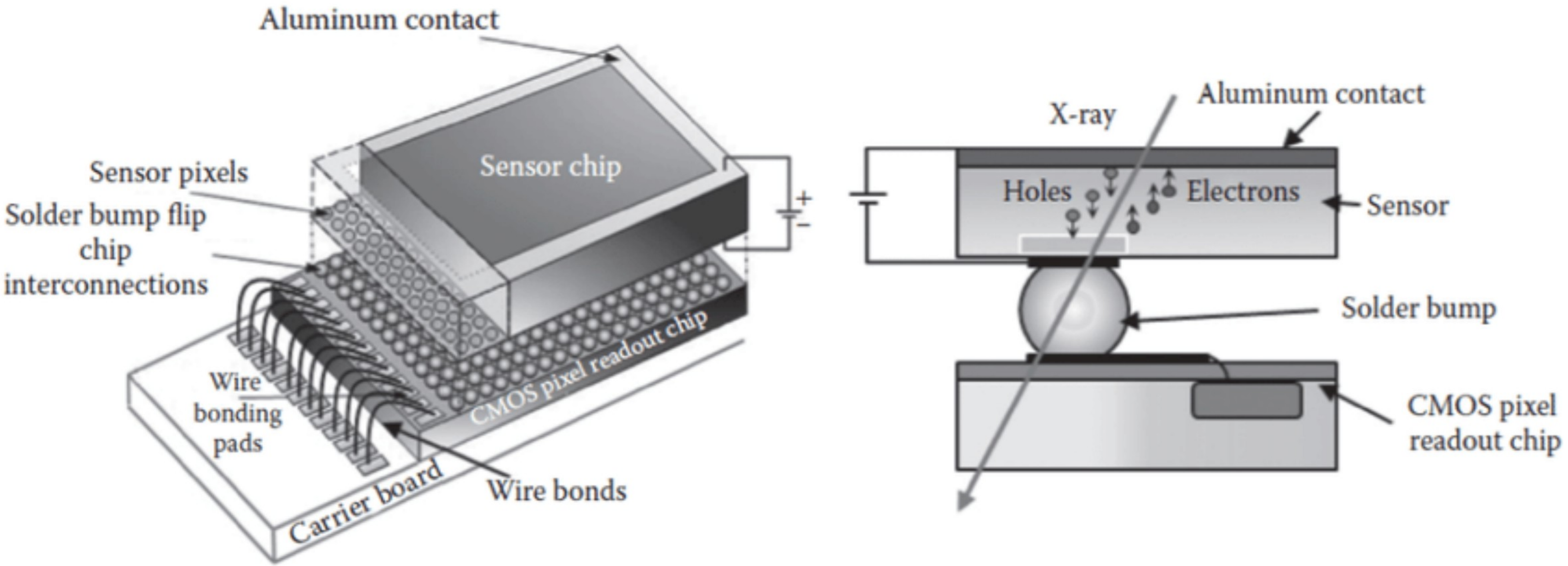


[Nat Rev Phys 1(2019)567]

Hybrid pixel detector

Need amplifier on top of each pixel: separate silicon wafer

- “bump bonding” to connect each implant to its amplifier



[http://cds.cern.ch/record/2706409]

Quiz

In a silicon detector, the doping concentration in the implants is

(a) much stronger than that of the bulk
(b) much less strong than that of the bulk

The thickness of the intrinsic depletion zone is determined by

(a) the doping concentration of the implant
(b) the doping concentration of the bulk

Silicon detectors are operated overdepleted to

(a) increase the signal amplitude
(b) reduce the length of the signal

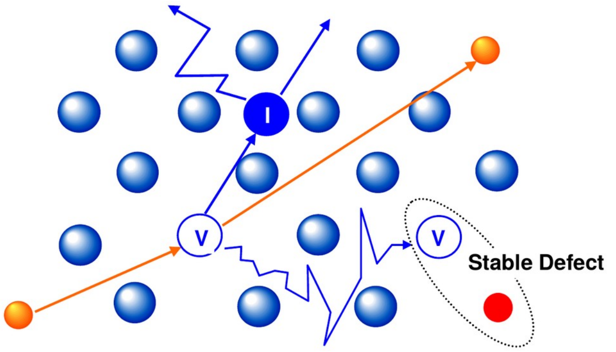
At the LHC, noise is dominated by contribution from

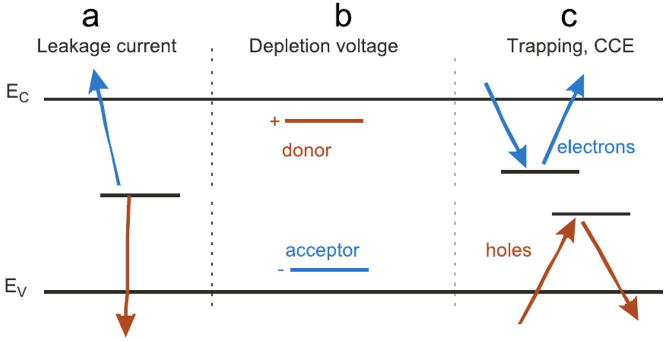
(a) statistical fluctuations in leakage currents
(b) charge fluctuations in resistors
(c) detector capacitance

Radiation damage in silicon

Non-Ionizing Energy Loss ("NIEL"): displacement of atoms in the lattice

- introduce energy levels inside band gap
  → **increase of leakage current**
- change in effective dopant concentration
  → **change in full depletion voltage**
- charge trapping
  → **loss of signal**





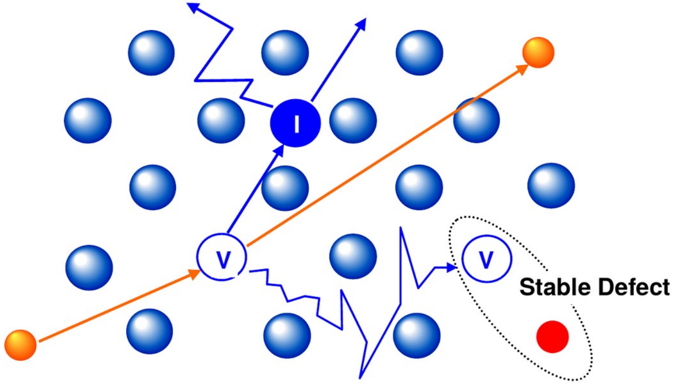
[NIM A666(2012)25]
[https://indico.cern.ch/event/635099/contributions/2570676/]

Beneficial and reverse annealing

Vacancies and interstitials diffuse through lattice

- “beneficial annealing”: recombination of a vacancy and an interstitial
- “reverse annealing”: combination with some detector impurity, formation of a stable defect (“Frenkel pair”)
- both are exponential as a function of time
  → time constants depend on temperature
  → reverse annealing much slower

operate at low temperature to suppress reverse annealing



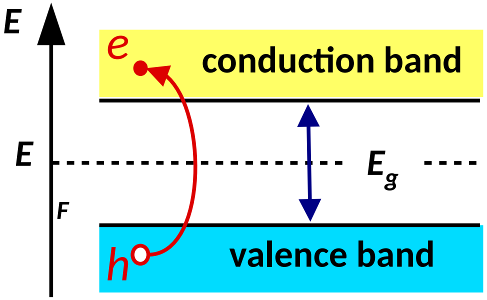
[https://indico.cern.ch/event/635099/contributions/2570676/]

Leakage current

Due to thermal excitation of *e*/*h* pairs

- before irradiation:

$$n_{th} \propto T^{3/2} \cdot \exp\left(-\frac{E_g}{2k_B T}\right)$$



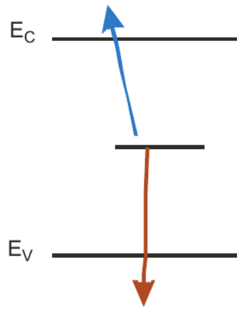
[https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8334647]

Leakage current

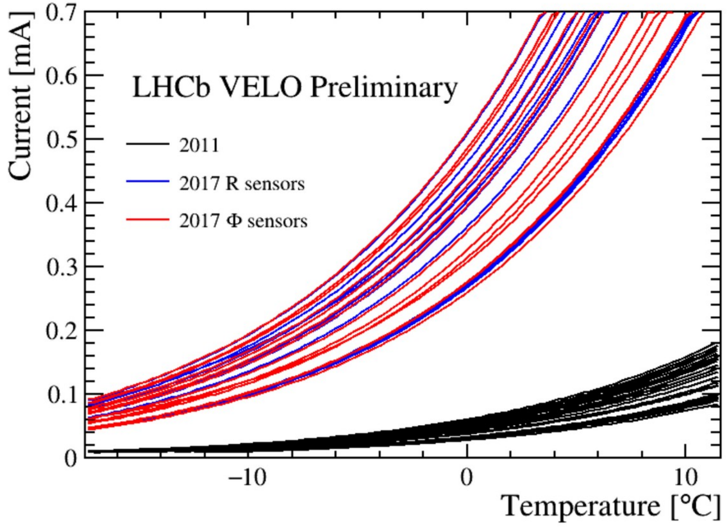
Due to thermal excitation of *e*/*h* pairs

- before irradiation:

$$n_{th} \propto T^{3/2} \cdot \exp\left(-\frac{E_g}{2k_B T}\right)$$



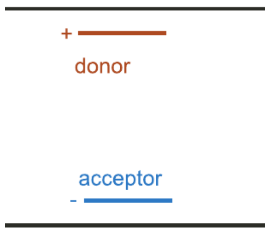
- radiation damage: energy states inside band gap → increase of leakage current
- can be suppressed by operating at low temperature
- about factor of 2 decrease per 7 °C



[https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8334647]

Full depletion voltage

Depends on dopant concentration in bulk



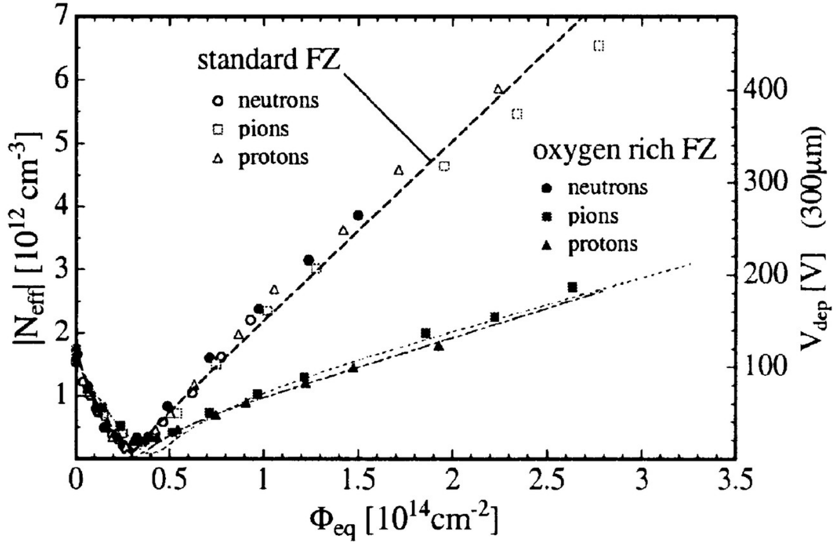
- before irradiation:

$$V_{fd} = \frac{e}{2\varepsilon} \cdot N_D \cdot D^2$$

- Frenkel pairs behave as acceptor atoms:

$$N_D \rightarrow N_{eff}$$

  (N_{eff} : “effective dopant concentration”)
- change in full depletion voltage
- *n*-type bulk: V_{fd} initially decreases, then increases after “type inversion”



[NIM A512(2003)30]

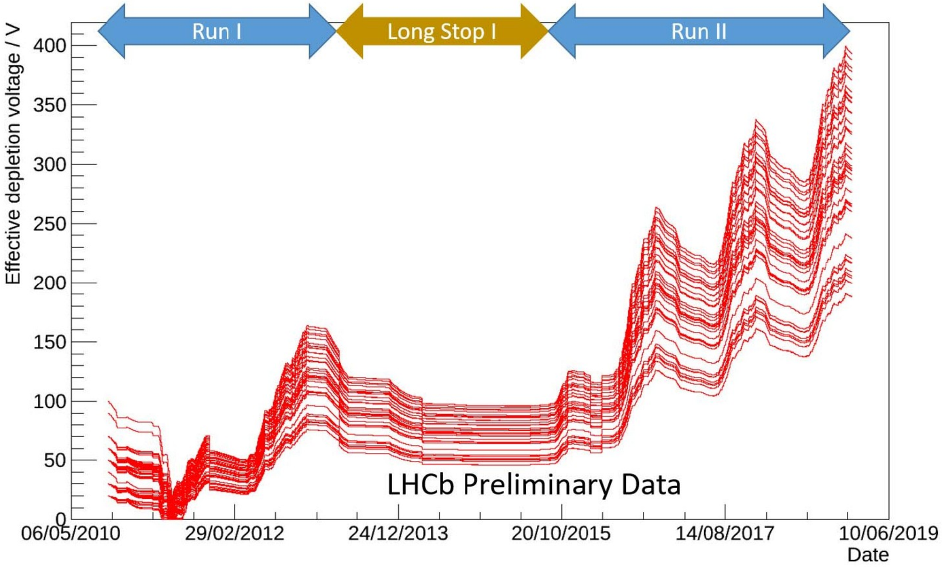
Full depletion voltage

Detector "dies" when V_{fd} exceeds breakdown voltage

- detector can no longer be fully depleted
  → loss of signal and efficiency

Hamburg model: calculate expected evolution of V_{fd}

- take into account particle fluence, beneficial and reverse annealing as a funtion of time and temperature



[https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8334647]

Improving radiation hardness

Operate at low temperature

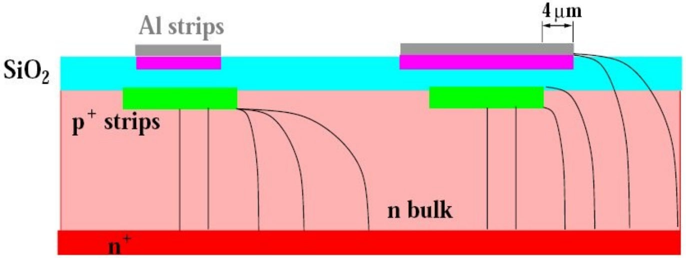
- suppress leakage current and reverse annealing

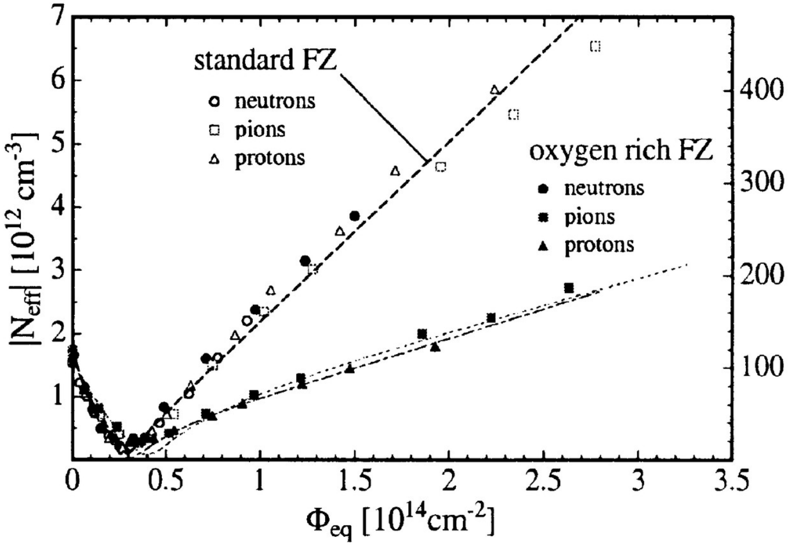
Detector material (e.g. oxygenization of silicon bulk**)**

- suppress formation of Frenkel pairs

Detector design

- maximize break-down voltage





[NIM A512(2003)30]

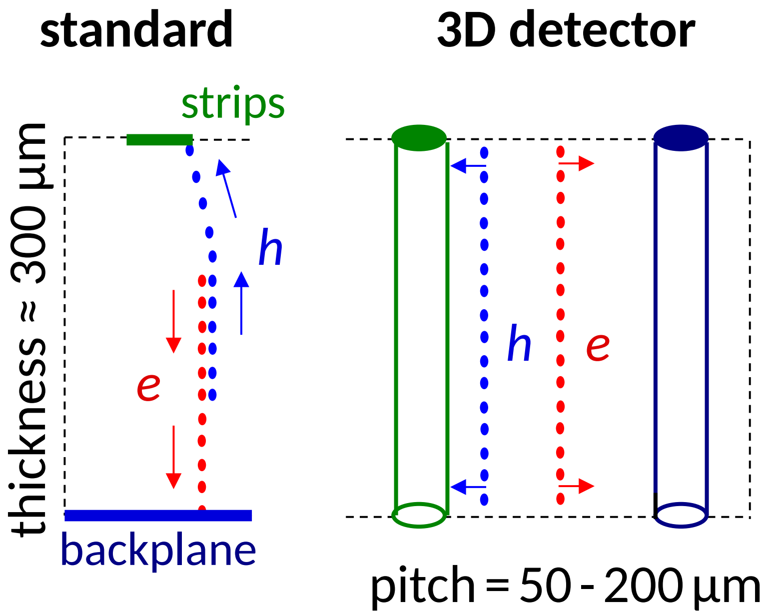
3D sensors

Conventional sensor: implants on the surface, charge carriers drift through thickness of bulk

- at very high fluence: significant signal loss from trapping of charge carriers at defects

3D sensor: implant columns through bulk

- shorter drift distances possible without having to reduce thickness of the bulk
  → same number of e/h pairs created
  → smaller loss from charge trapping



3D sensors

Columns can be connected together

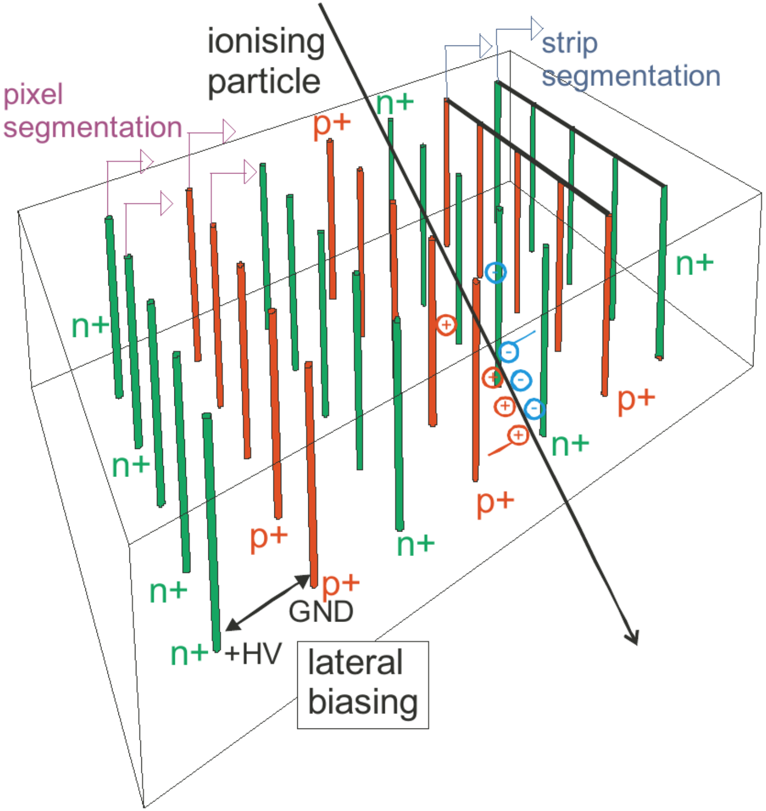
- segmentation into pixels or strips

Processing still expensive

- laser drilling or etching of columns

First application in ATLAS “Insertable Barrel Layer”, installed 2013/2014

- 112 detector modules
- 2 cm × 2 cm per module

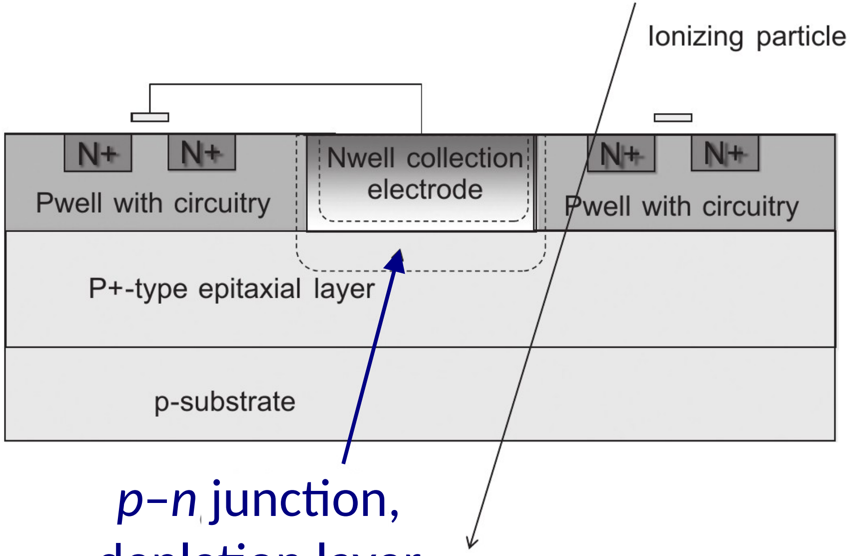


Monolithic Active Pixel Sensors (MAPS)

Integrate sensor and front-end electronics in one wafer

- no need for bump bonding → simpler & cheaper
- smaller capacitance → lower noise → thinner detectors
- but: conventional NMOS/CMOS circuits do not allow to apply high bias voltages
- only thin depletion layer

→ charge collection mostly by diffusion
→ slow (limits rate capability)
→ charge trapping (radiation damage)



p–*n* junction,
depletion layer

[NIM A765(2014)167]

HV-MAPS

Use industrial HV-CMOS process (Power-Integrated Circuits**)**

- allows to apply voltages up to ≈ 100 V
- first application foreseen in µ3e experiment at PSI

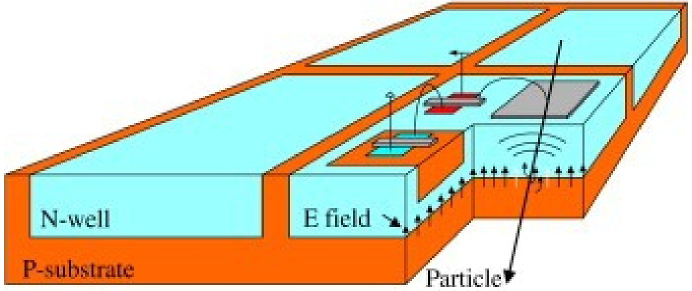
  → search for the decay $\mu^+ \rightarrow e^+ e^- e^+$

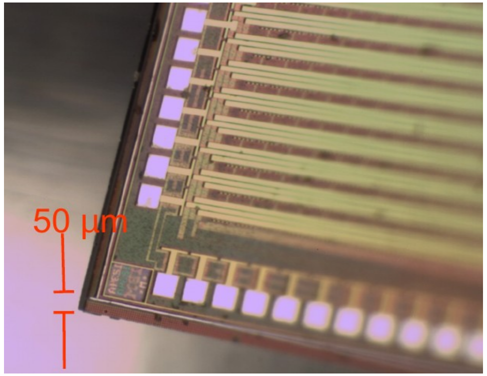
    → violates lepton number

    → forbidden in the Standard Model

  → μ^+ decays at rest → $e^\pm$ momenta very small

  → low material budget even more important
- thickness ≈ 50 µm, pixels 80 µm × 80 µm
- **summer 2020: R&D starting for LHCb Upgrade II**





Tracking with time resolution

Video of the lecturer

Measure time as well as position to improve pattern recognition:

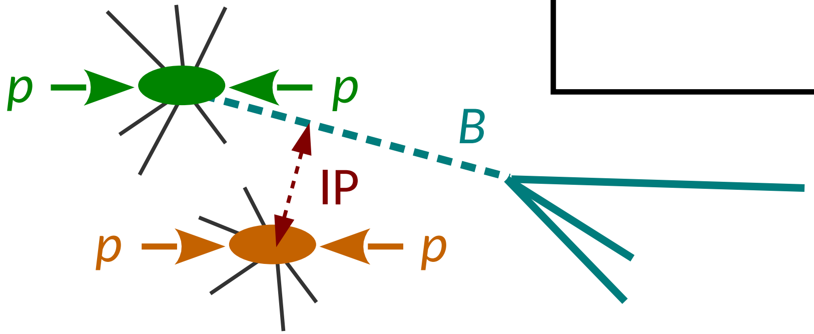
- assigning detector hits to tracks
- assigning tracks to vertices

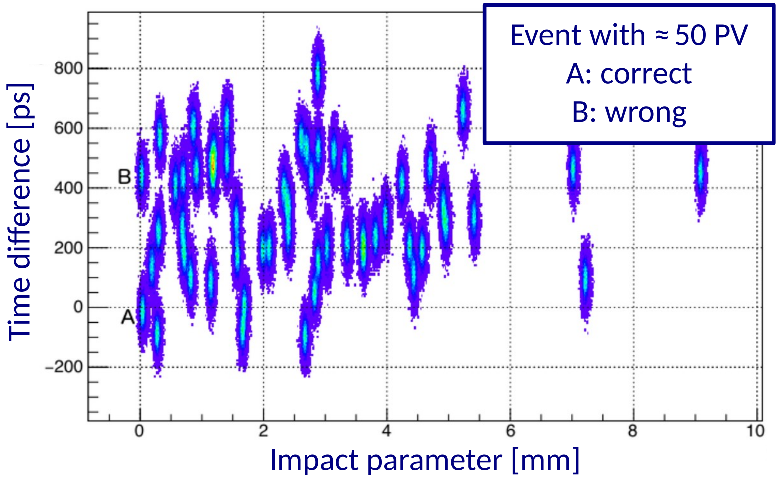
Example: LHCb measures *B* mesons

- travel ≈ 1 cm before they decay, need to assign them to the correct *p*–*p* collision
- standard tracking: use impact parameter

Upgrade 2: around 50 *p*–*p* collisions / event

- impact parameter alone maybe not good enough, time information could help





[LHCb-PUB-2019-001]

Low-Gain Avalanche Detectors (LGAD)

Introduce thin, highly doped "gain layer" underneath each readout implant

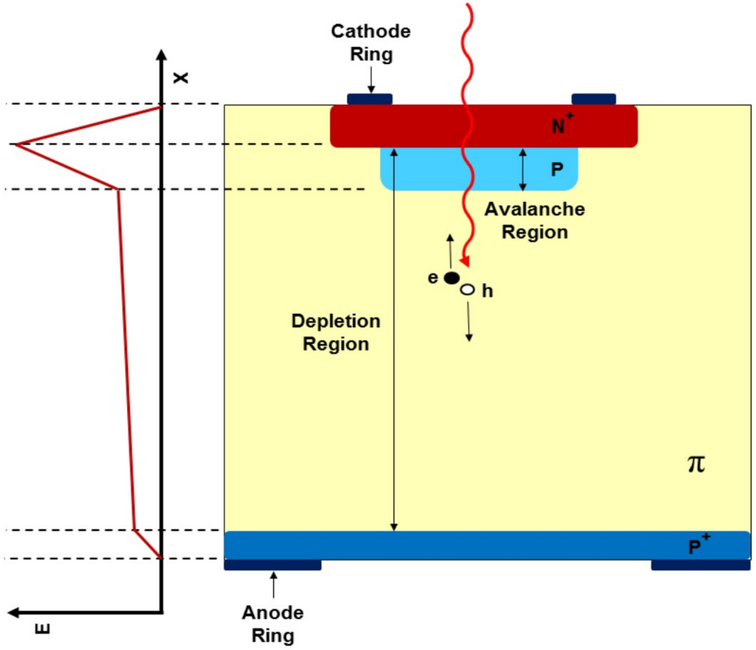
- high electric field → charge avalanche

Large signal with thin detector

- excellent time resolution,
- ≈ 30 ps measured for $1.3 \times 1.3\ \text{mm}^2$ pixels

R&D required

- time resolution for small pixels
  → non-uniform electric field, drift velocity
- radiation hardness ?

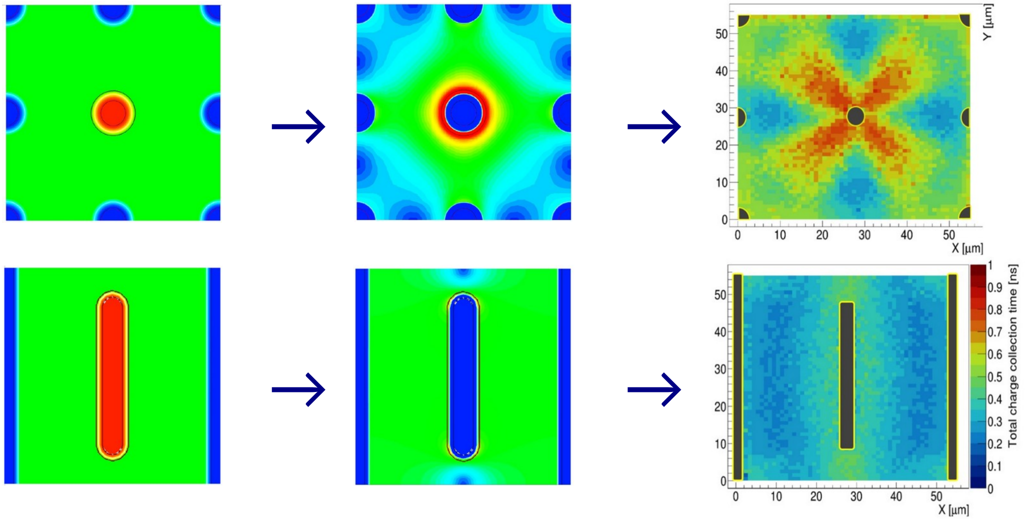


[Giovanni Pellegrini @ 23rd RD50]

"3D" detectors

Short drift distance → fast signal collection

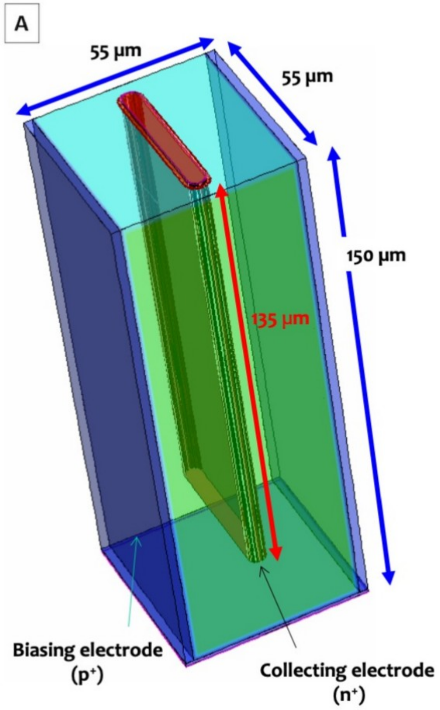
- new idea: implant "trenches" instead of columns
- measured < 20 ps time resolution on prototypes



Columns → →

Trenches → →

doping field signal collection time



[arXiv:2004.10881]

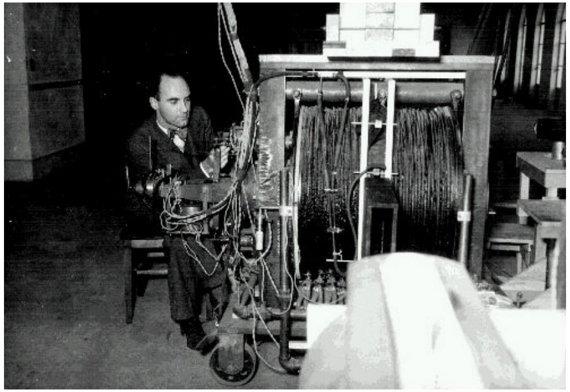
New Technologies for New Physics

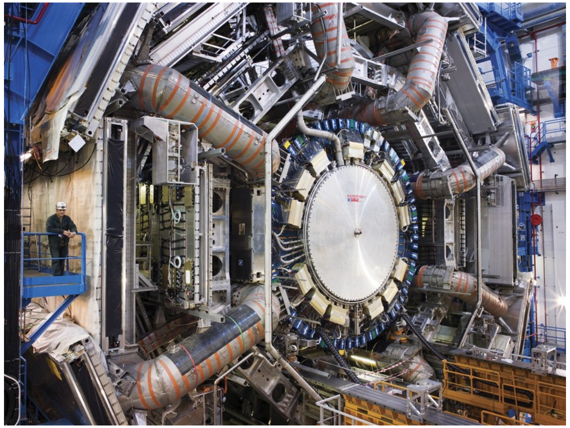
Impressive evolution in particle tracking detectors

- from Cloud Chamber to silicon, HV-MAPS, 3D, …

Driven by increasingly challenging requirements

- rate capability, granularity, radiation hardness, time resolution, …





> *The great advances in science usually result from new tools rather than from new doctrines.*
> Freeman Dyson (1923-2020)