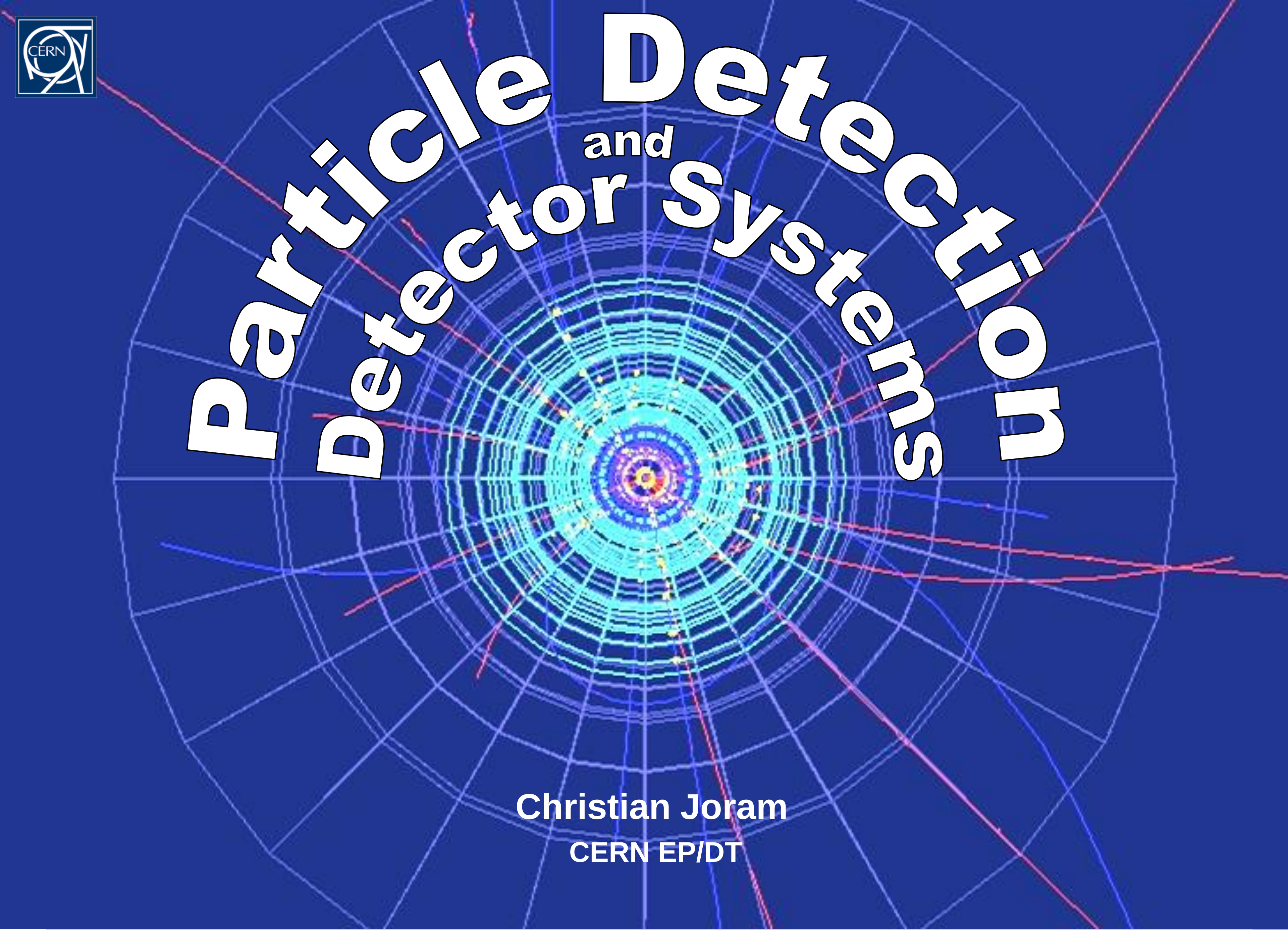
# Particle Detection and Detector Systems




**Christian Joram**

**CERN EP/DT**

# Particle Detection and Detector Systems

- Elementary particles
  - properties, list of detectable particles

- What can be measured ?
  - - detection of the presence of a particle --> Counter
  - - charge (+/-/0)
  - - track of a particle (position, direction)
  - - momentum → magnetic field
  - - energy → calorimeter
  - - mass = identity

- Principles of particle detection
  - - ionisation of gases → Geiger counter → wire chambers → drift chambers
  - - ionisation of solids → Silicon detectors → micro strip & pixel detectors
  - - excitation of matter → scintillation counters
  - - calorimetry
  - - Cherenkov effect

# Outline (cont.)

- **Detector systems**
  - principles
  - some examples: CMS, ATLAS
  - materials and practical considerations

If there is time left …

- **LHCb SciFi Tracker (my current project)**

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# Introduction

## Elementary particles – what are they and where do they come from ?

Current understanding: Everything started with a BIG BANG (~13.8 billion years ago)

→ All matter and radiation (but also space and time) were created

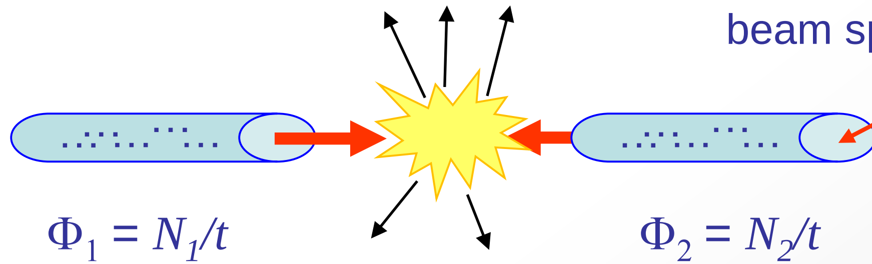
Today, directly around us, we see a ‘cold’ world, made from stable atoms, without free elementary particles … except of

- photons = light
- elementary particles produced in radioactive decays of nuclei (natural, power plants, atomic bombs)
- elementary particles from extra-terrestric sources (sun, super novae, …)
- elementary particles produced by accelerators e.g. LHC

# Production of elementary particles in an accelerator experiment

Option 1: colliding 2 particle beams

What is the interaction rate $R_{int.}$ ?

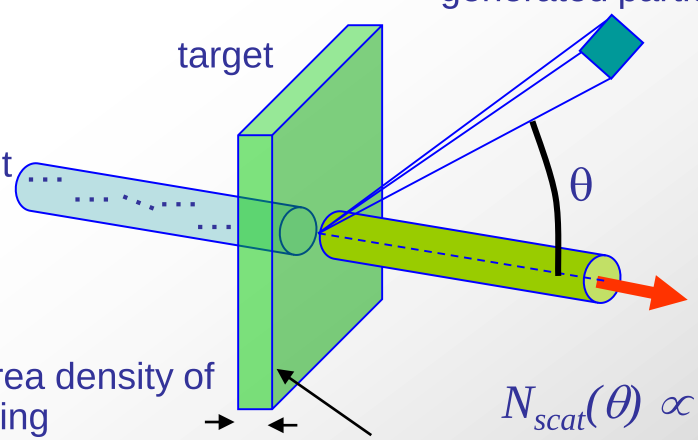



$$R_{int} \propto \underbrace{N_1 N_2 / (A \cdot t)}_{\text{Luminosity } L \ [\text{cm}^{-2}\,\text{s}^{-1}]} = \sigma \cdot L$$

Luminosity $L$ [cm$^{-2}$ s$^{-1}$]

cross sections $\sigma$ (physics)

Option 2: Shooting on a target




$n_A$ = area density of scattering centres in target

d

$$N_{scat}(\theta) \propto N_{inc} \cdot n_A \cdot d\Omega$$

$$= d\sigma/d\Omega(\theta) \cdot N_{inc} \cdot n_A \cdot d\Omega$$

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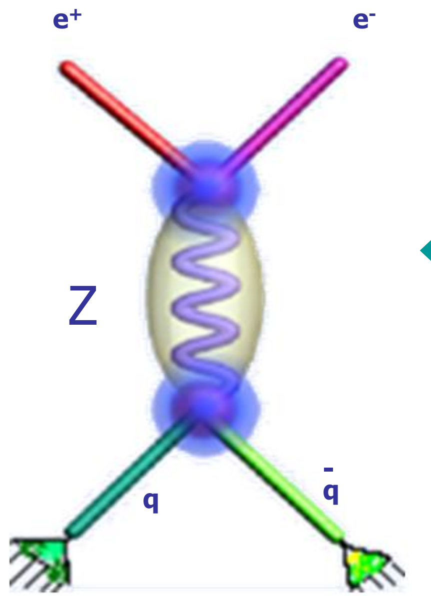
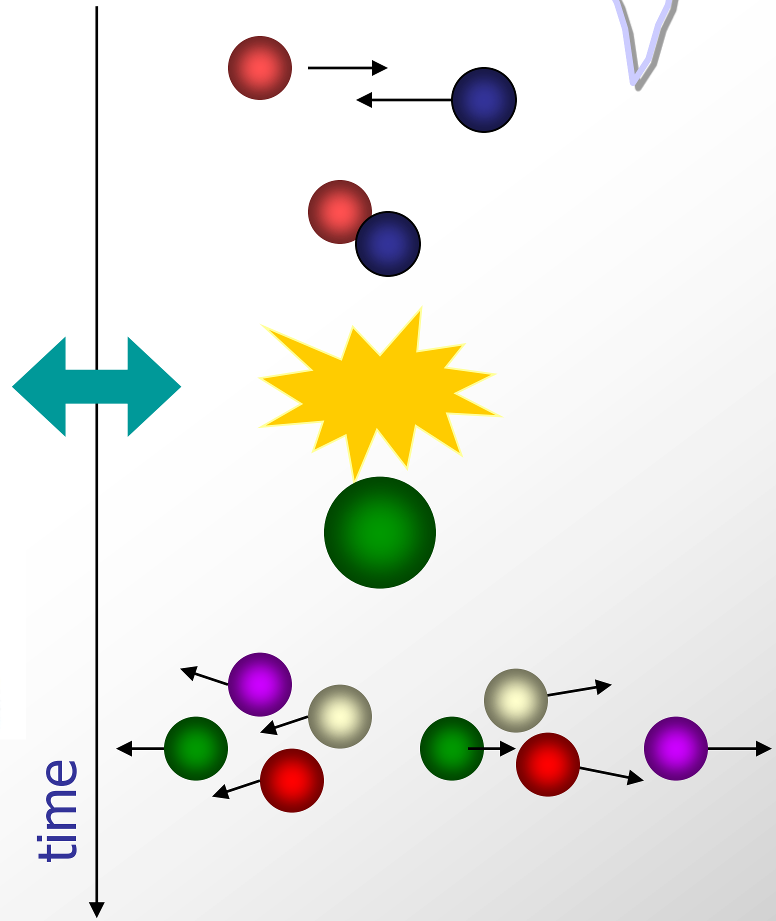
# Introduction

Idealistic views of an elementary particle reaction (e.g. in LEP or CLIC)

$$e^+ + e^- \rightarrow Z^0 \rightarrow q\bar{q}$$

$$(+\,\text{hadronization})$$




- Usually we can not ‘see’ the reaction or the Z-boson itself, but only the end products of the reaction.
- Reconstruct the reaction mechanism and the properties of the involved particles → we need the maximum information about the end products !

# Introduction

## Higgs production (in the macroscopic world)

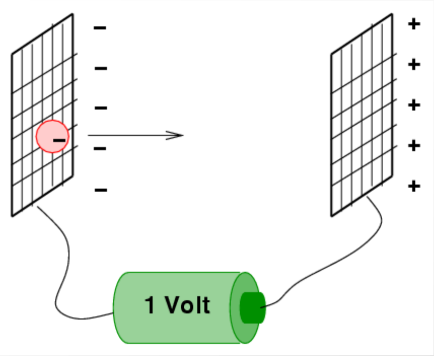
time

# Mass and Energy of elementary particles

- In the 'normal' world, **mass** and **energy** are measured in **kg** and **Joule** (= Watt·s).
- Also elementary particles can be measured with these units, but it's unpractical, because the units are too large.
- Instead, we use both for **energy** and **mass** the unit 'electron volt' (eV).

$E = mc^2$

For the physicists … $$E^2 = \vec{p}^{\,2}c^2 + m_0^2 c^4$$




1 eV is a tiny portion of energy. 1 eV = $1.6 \cdot 10^{-19}$ J

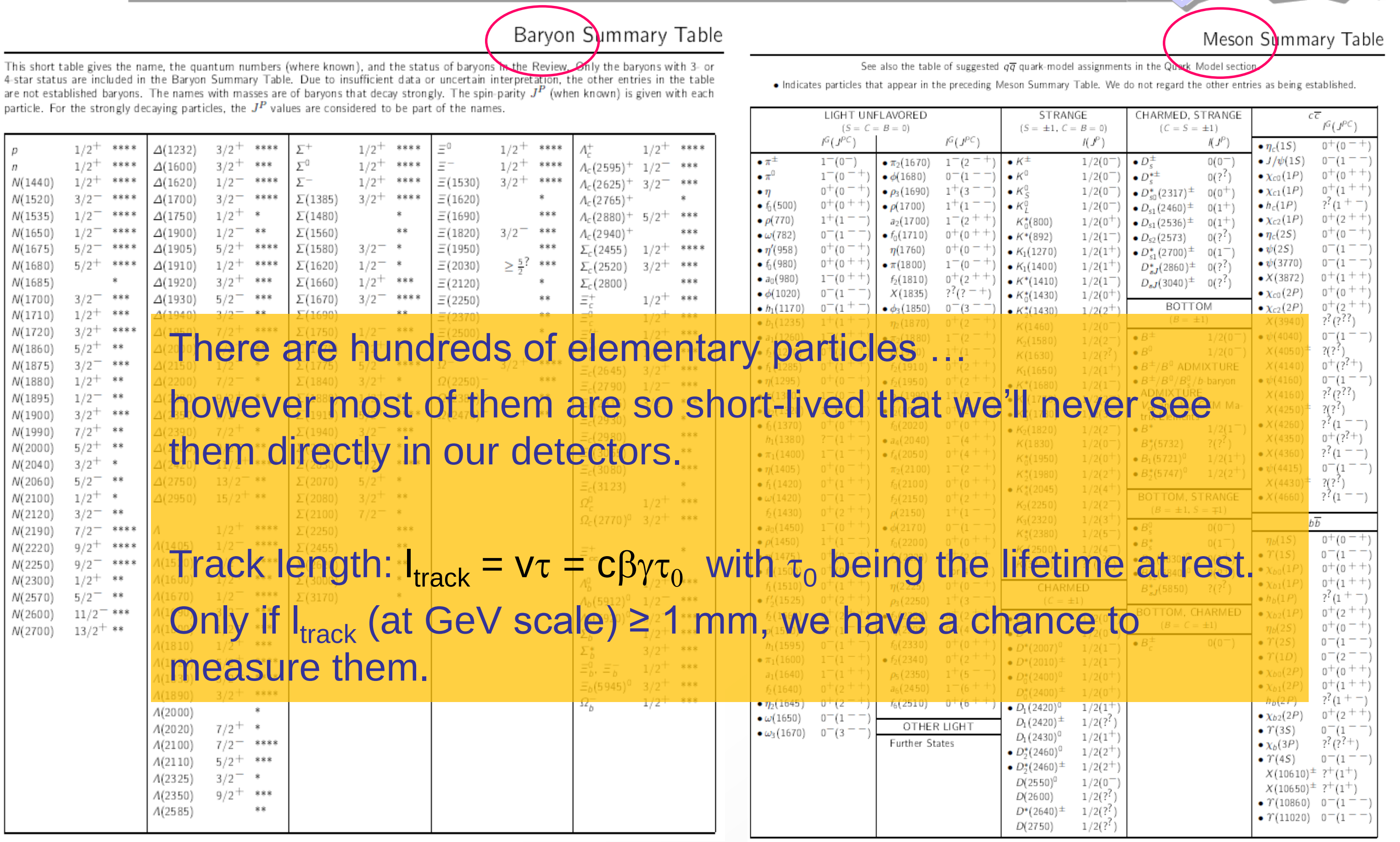
$m_{bee}$ = 1g = $5.8 \cdot 10^{32}$ eV/$c^2$

$v_{bee}$= 1m/s $\rightarrow$ $E_{bee}$ = ½ m·$v^2$ = $10^{-3}$ J = $6.25 \cdot 10^{15}$ eV

$E_{proton,LHC}$ = $7 \cdot 10^{12}$ eV

- typical particle masses are 1 – 100 GeV,
- typical particle energies are in the range MeV, GeV, TeV

# Introduction




There are hundreds of elementary particles …
however most of them are so short-lived that we'll never see them directly in our detectors.

Track length: $l_{track} = v\tau = c\beta\gamma\tau_0$ with $\tau_0$ being the lifetime at rest.
Only if $l_{track}$ (at GeV scale) ≥ 1 mm, we have a chance to measure them.

**Leptons**
- e
- $\mu$
- $\tau$
- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

**Gauge bosons**
- $\gamma$
- $W^{+/-}$
- Z
- g
- H

Which are left then? These 8 particles (and their antiparticles).

| | $\gamma$ | p | n | $e^\pm$ | $\mu^\pm$ | $\pi^\pm$ | $K^\pm$ | $K_0$ ($K_S/K_L$) |
|---|---|---|---|---|---|---|---|---|
| $\tau_0$ | ∞ | ∞ | ∞ | ∞ | 2.2μs | 26 ns | 12 ns | 89 ps / 51 ns |
| $l_{track}$ (p=1GeV) | ∞ | ∞ | ∞ | ∞ | 6.1 km | 5.5 m | 6.4 m | 5 cm / 27.5 m |

# What can we measure ?

**Presence of a particle** → Geiger counter


1 particle = 1 click

**Electric charge** (+ / - / 0)

→ observe deflection of particle beam in magnetic or electric fields

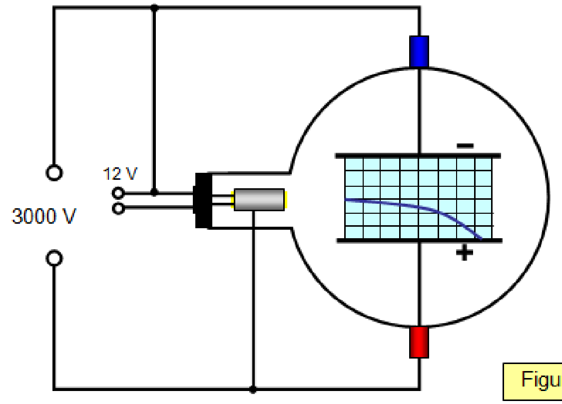
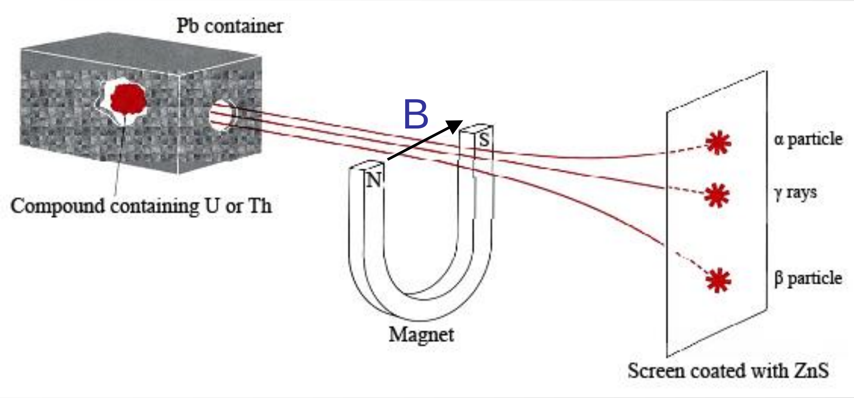



Figure 2




$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

*Electric force* *Magnetic force*

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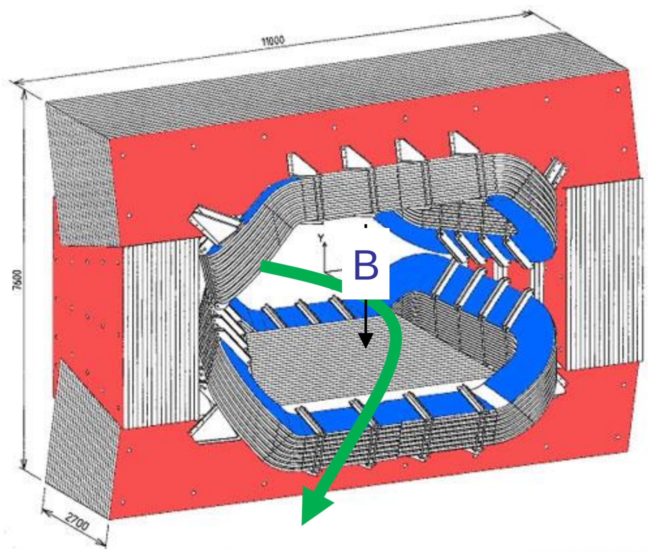
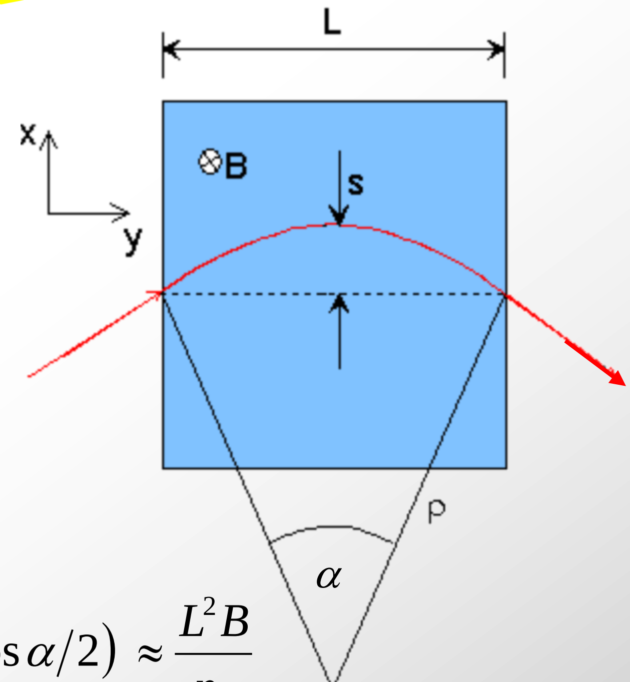
# What can we measure ?

**Momentum *p***

Works only for charged particles!

Measure the radius of curvature $\rho$ in a magnetic field

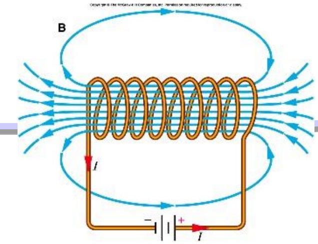


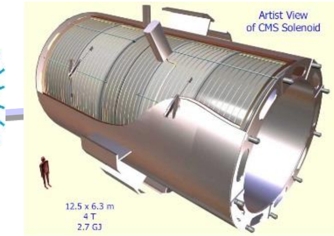



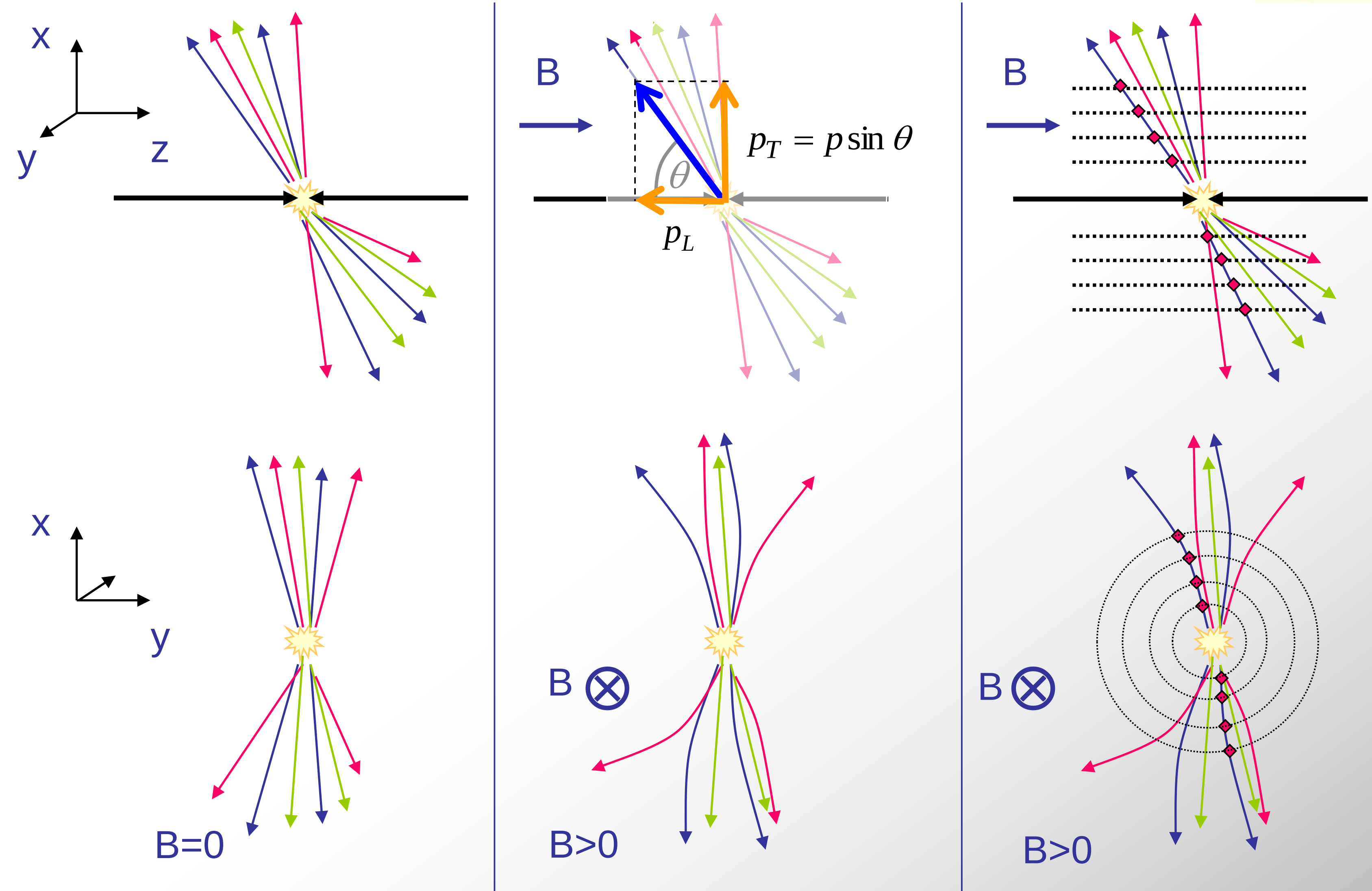

$$s = \rho(1 - \cos\alpha/2) \approx \frac{L^2 B}{p_T}$$

- sagitta *s* needs to be sufficiently large to be measureable with good precision
- if p is large, also B and/or L need to be large
- and we need a detector which can measure the **track**

# Momentum measurement in a solenoid magnet

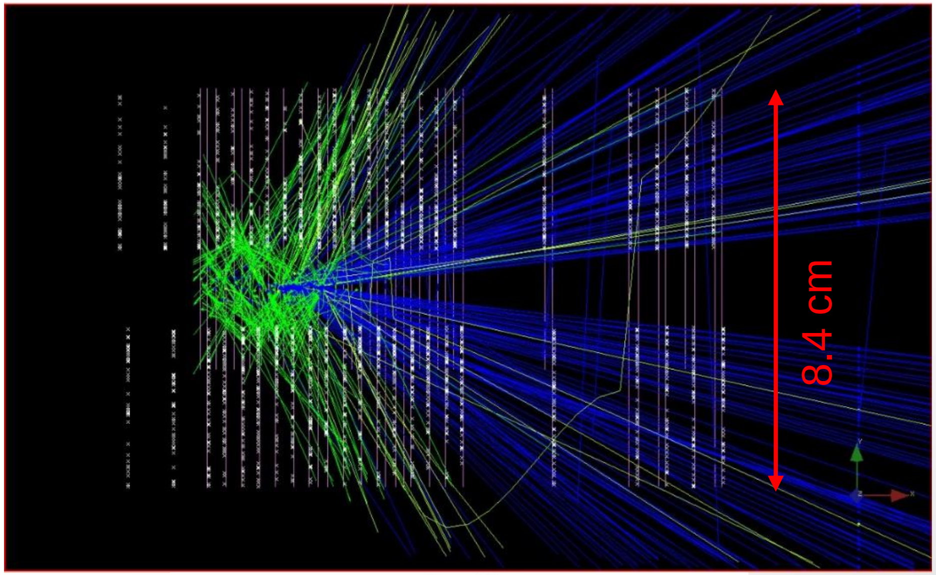


# What can we measure ?

Example LHCb VELO detector




**Track of a particle**

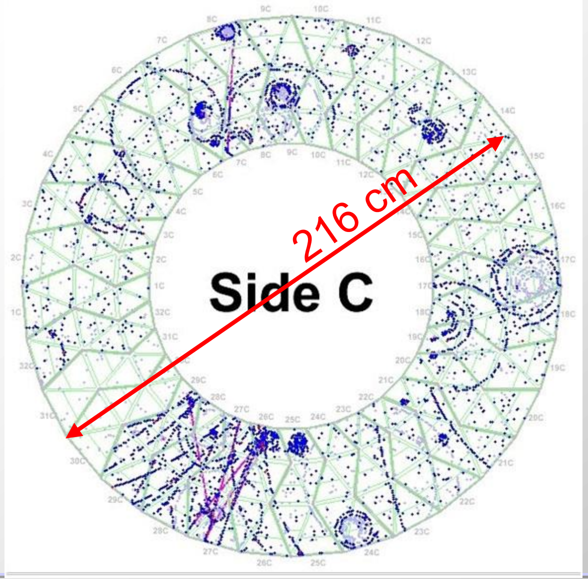
Momentum measurement requires precise knowledge of position and angles of a particle.

Many particles may need to be tracked at the same time.

→ Need detectors with high granularity, several detection planes

→ many readout channels.

ATLAS TRT

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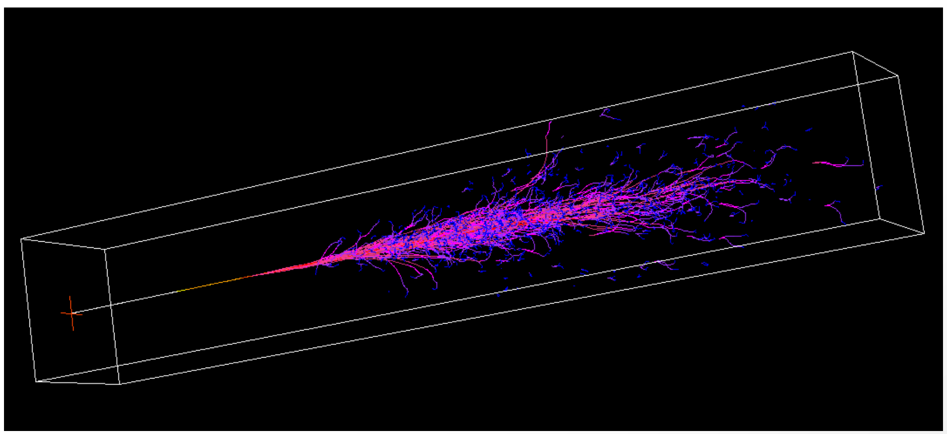
# What can we measure ?

**Energy of a particle** (not the same as momentum $E^2 = \vec{p}^2 c^2 + m_0^2 c^4$ )

A high energy particle hitting a block of material creates a shower of low energy particles. These are all stopped in the block. Their energy is summed up and (after proper calibration) gives the energy of the initial particle.



Simulation of a shower created by a 24 GeV electron in a block of Iron.

works both for charged and neutral particles and for high energy photons

This method of energy measurement is called calorimetry. The method is destructive! The particle is stopped in the calorimeter.

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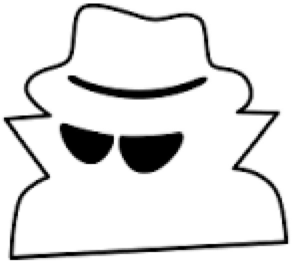
# What can we measure ?

**Identity of a particle**



Some particles have the same charge, spin and other properties.

To distinguish them, one can use

- Particle mass. Different particles have different masses.
- Lifetime. Different particles have different lifetimes.
- Type of interaction with matter

We'll come back on this a bit later!

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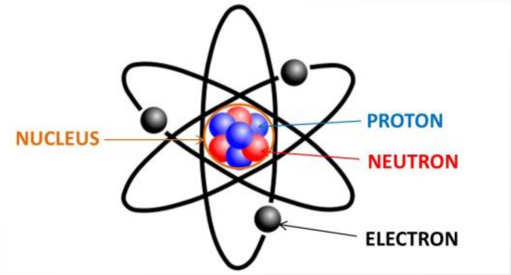
# What happens when particles pass through matter ? (solid, liquid, gas)

- **They loose energy**
- **They scatter**

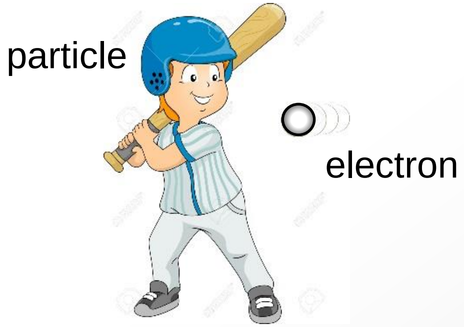
Matter is made from atoms = nuclei + electrons

normally much heavier than the particle (nuclei)

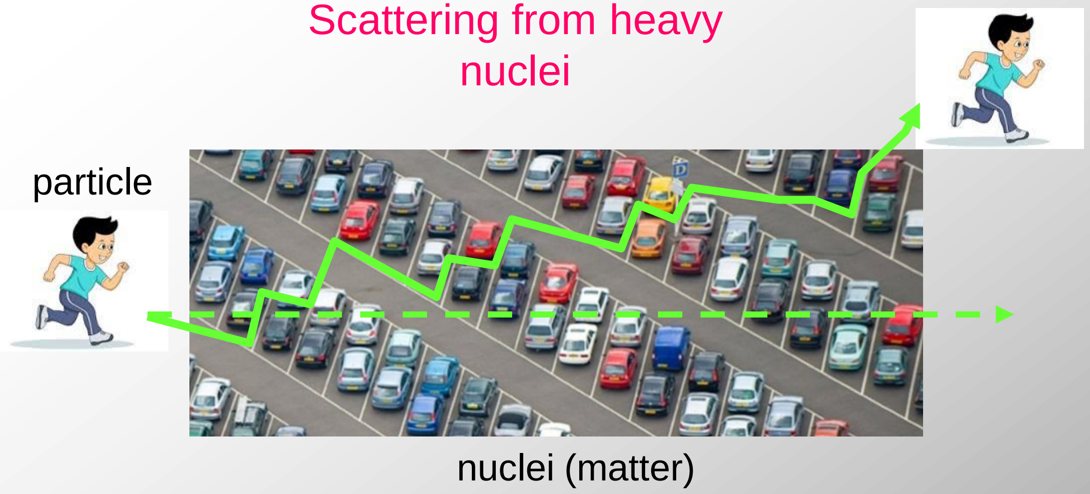
normally much lighter than the particle (electrons)




Energy loss by energy transfer to light electrons

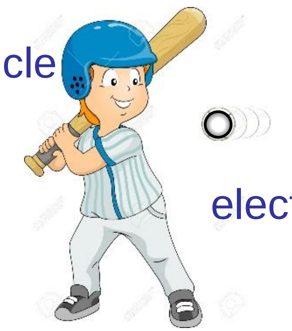



Scattering from heavy nuclei

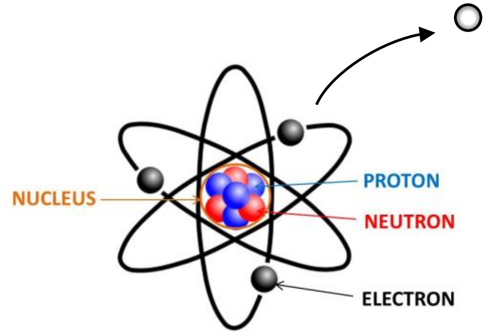


## Energy loss by energy transfer to electrons

Particle



electron



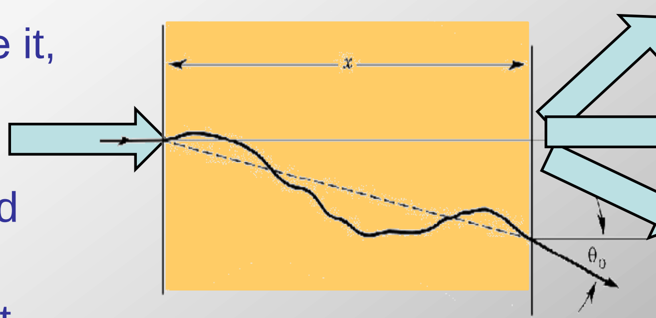

(free) electron(s) =

**ionisation or excitation of matter**

- In the extreme case, a single free electron can evidence the interaction of a particle with matter!
- How do we make the electrons visible? How do we produce a ‘signal’?

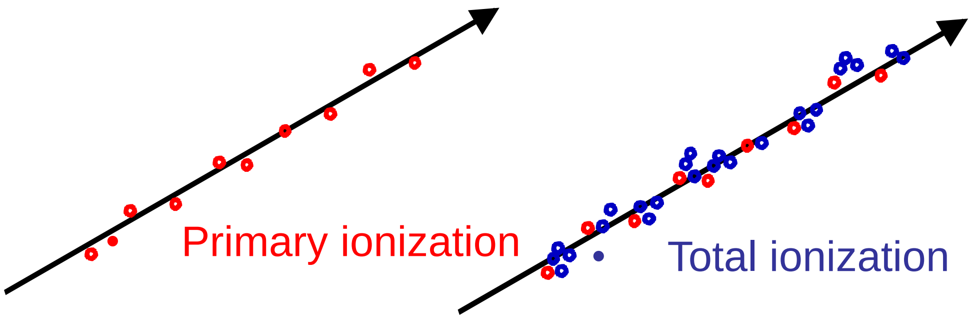
## Scattering from the heavy nuclei

- Scattering is unavoidable, but we normally don’t like it, because scattering smears the particle tracks.
- Dense media (steel) give more scattering than light ones (gas). Low energy particles are more scattered than high energy ones.
- We want to build tracking detectors from the lightest materials (e.g. CF composite).

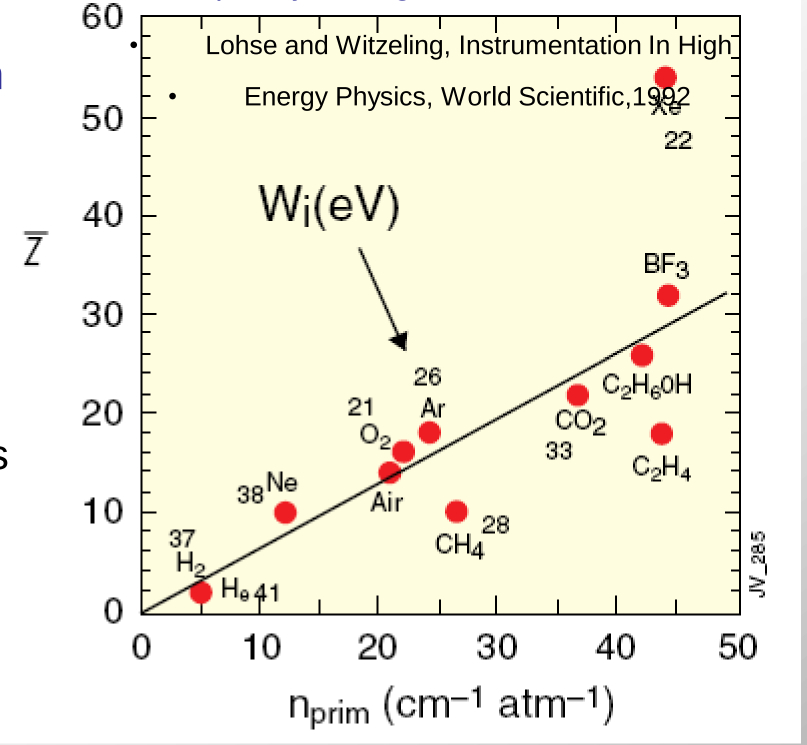


# Gaseous detectors

- Fast charged particles ionize atoms of gas.



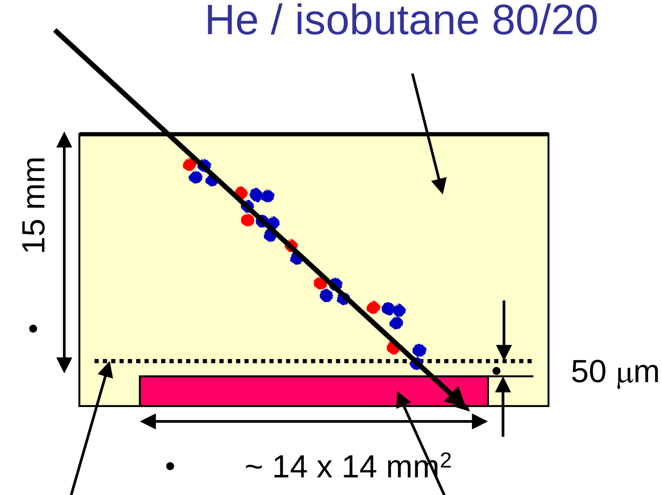

Number of primary electron/ion pairs in frequently used gases.

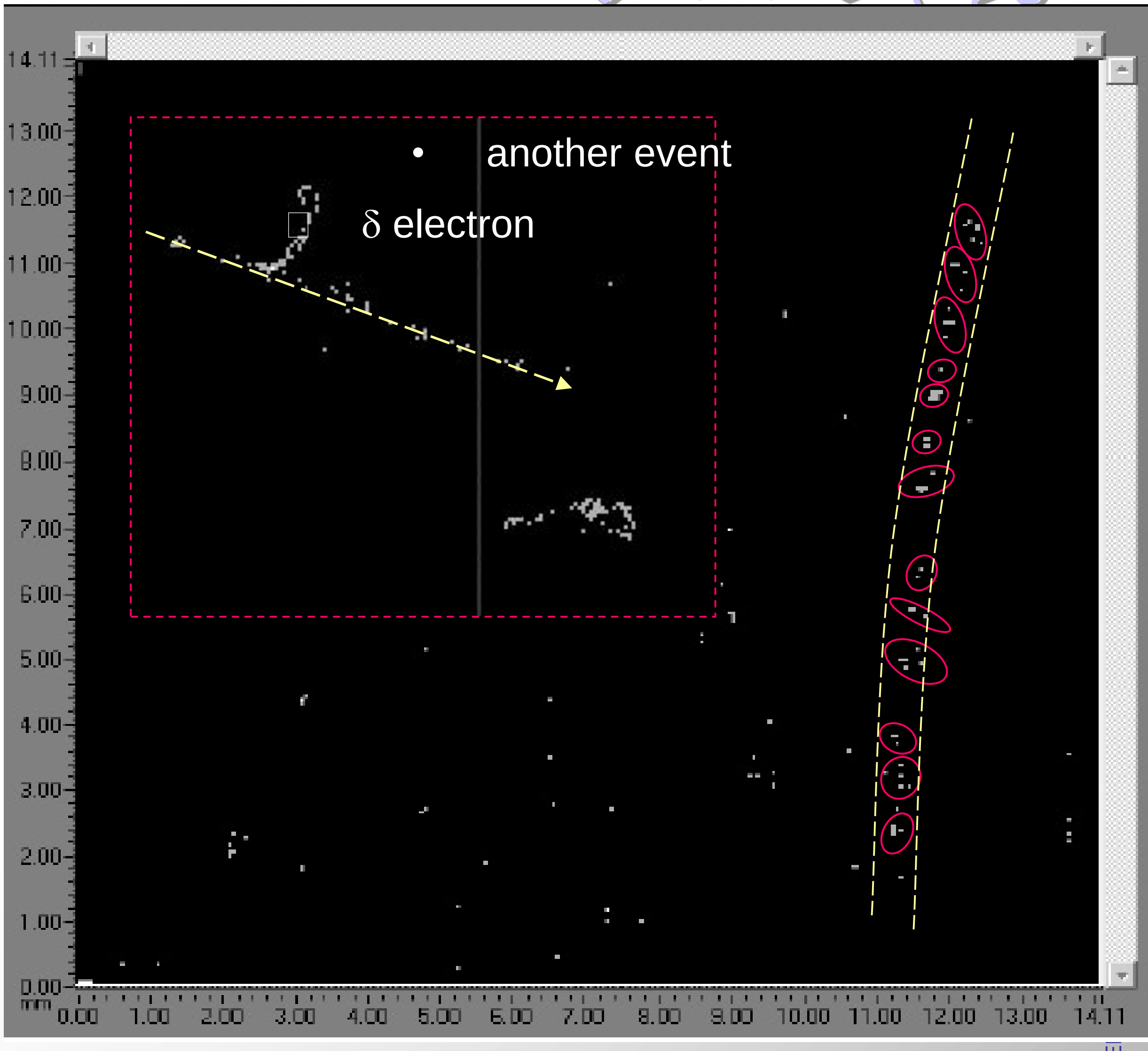



- Often, the resulting primary electrons will have enough kinetic energy to ionize other atoms.
- $N_{total} = (3…4) \times N_{primary}$
- 1 cm Ar gas → 25 primary electron/ion pairs

  → 100 e/ion pairs in total

Observing ionization clusters with a hybrid gas detector: pixel readout chip + micromegas



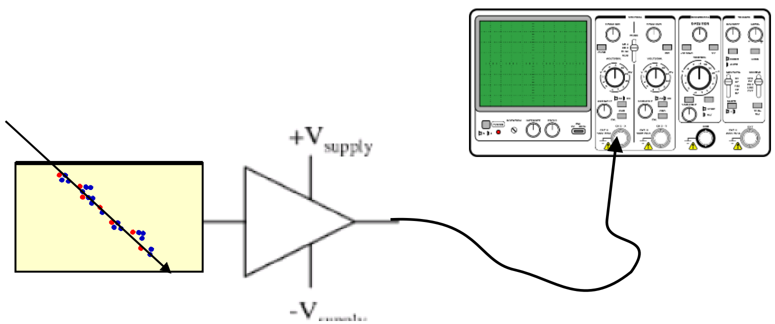



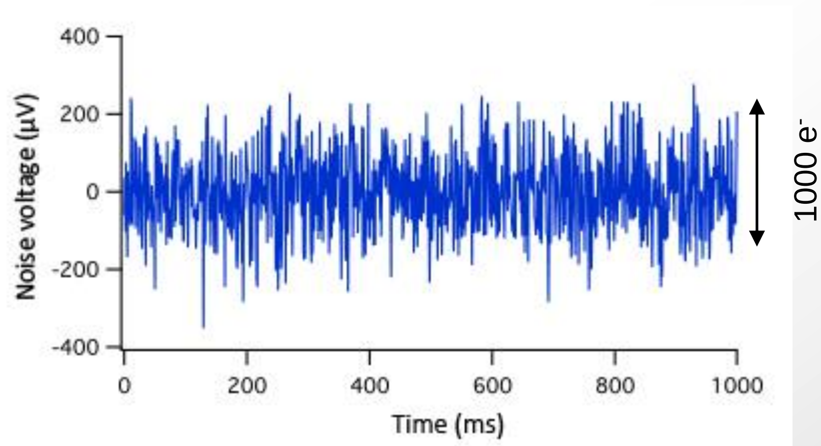

M. Campbell et al., NIM A 540 (2005) 295

track by cosmic particle (mip): 0.52 clusters / mm, ~3 e⁻/cluster

100 electrons/ion pairs created during ionization process are not easy to detect.

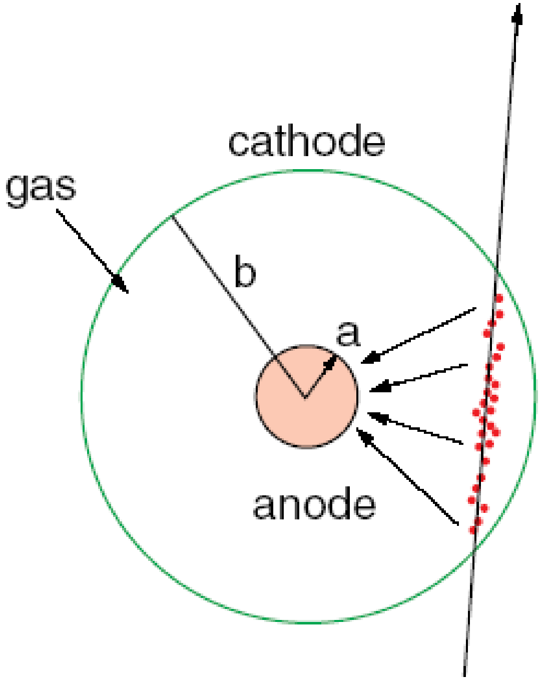
Typical (equivalent) noise of an electronic amplifier ≈ 1000 $e^-$

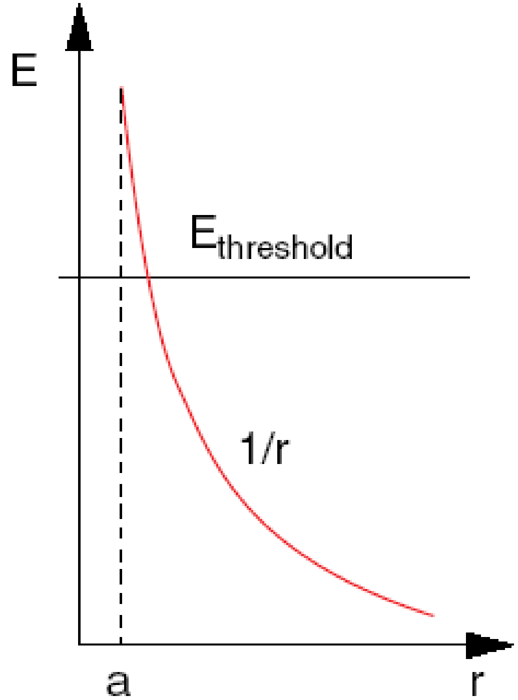



→ we will increase the number of charge carriers by **gas amplification** .

# Principle of Geiger Mueller counter

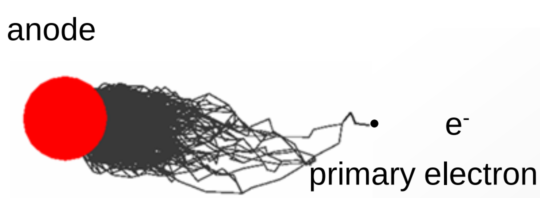


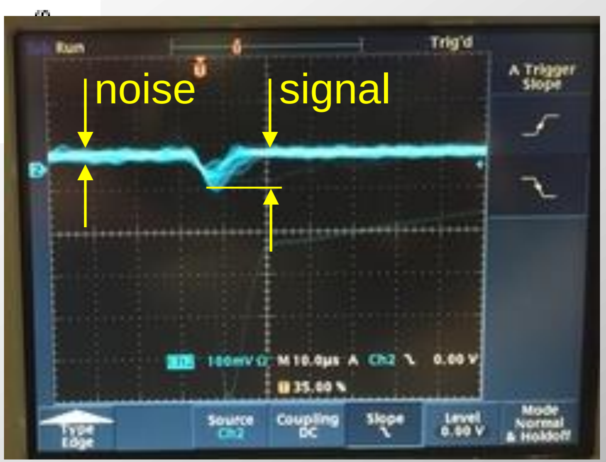




Close to the wire, the electrons get enough energy to ionise other gas atoms.

1 electron can produce thousands or even millions of electrons.

The signal becomes detectable!




Not shown here, but important: the gas ions drifting away from the wire, produce the main part of the signal.

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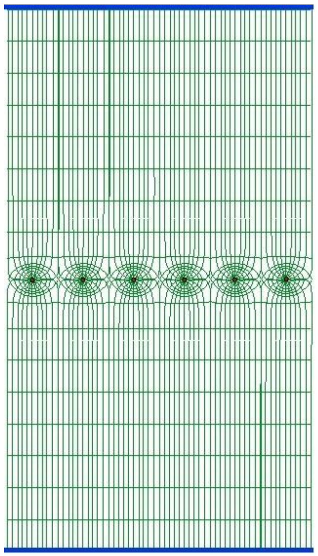
# Multi Wire Proportional Chamber (MWPC)



- Simple idea 'in principle': Multi Wire Proportional chamber (MWPC)
- Nobel  Prize 1992
- First electronic device allowing high statistics experiments !!

Typical geometry

5mm, 1mm, 20 μm

Normally digital readout :

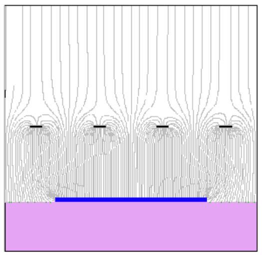
spatial resolution limited to

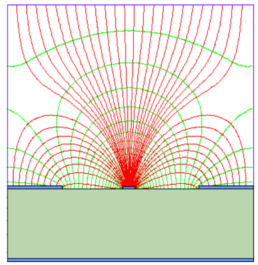
$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

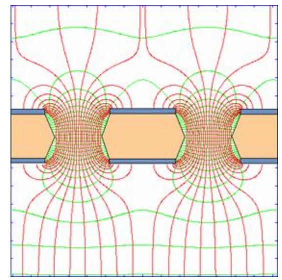
for d = 1 mm $\sigma_x$ = 300 μm

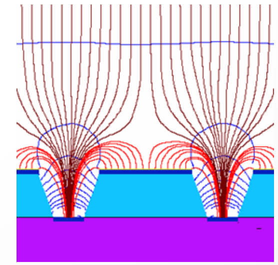

G. Charpak, F. Sauli and J.C. Santiard

Cylindrical geometry is not the only one able to generate strong electric field:

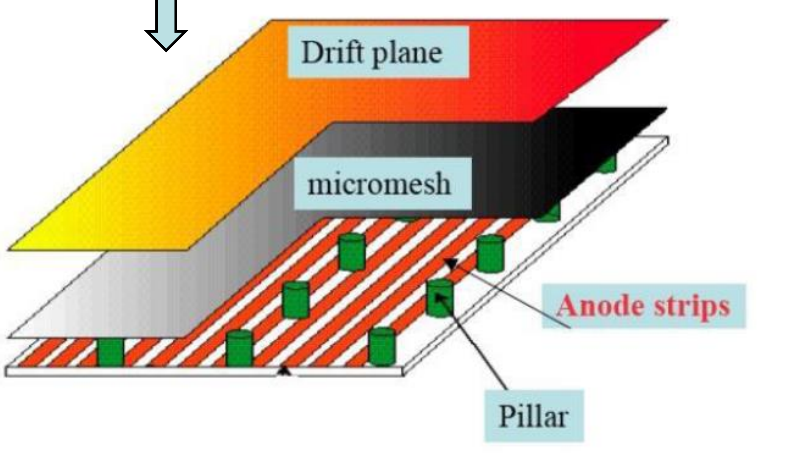

parallel plate


strip

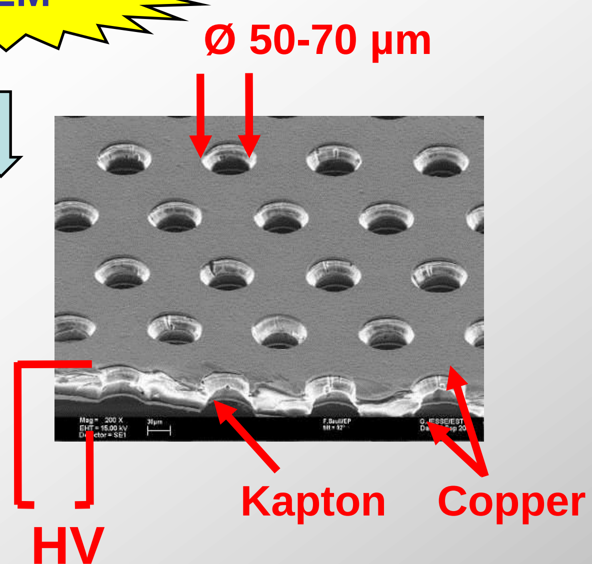

hole


groove

**MicroMegas**




**GEM**

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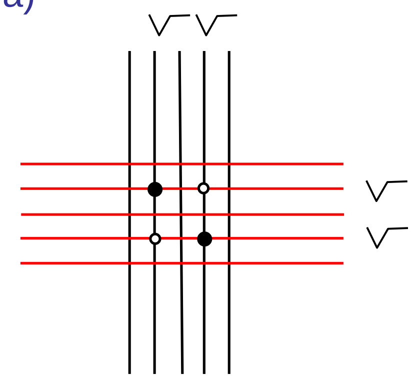
# From 1D to 2D detectors

a)

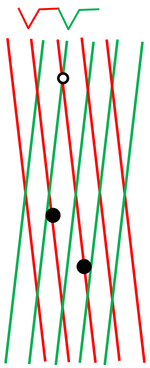


Crossed wire plane

→ 2N channels

However: ghost hits (≥2 particles)

b)



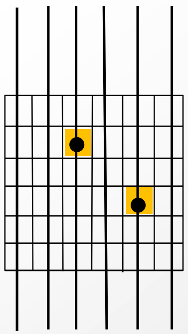
Stereo geometry (e.g. ±5°)

→ 2N channels.

One coordinate has worse resolution than other.

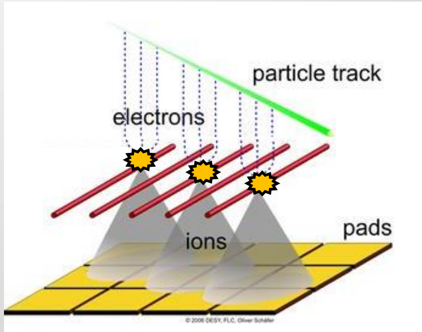
Ghost hits only local.

c)



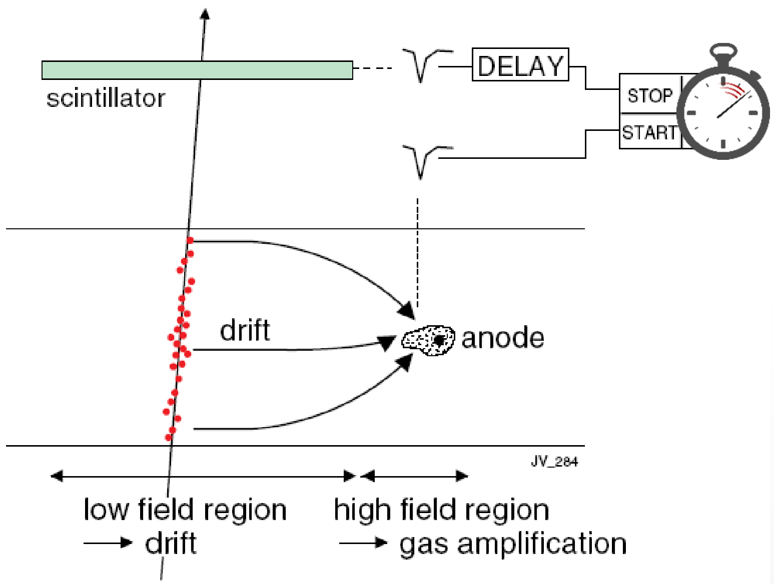
True 2D readout. Signals from wires are induced on readout plane just behind wires.

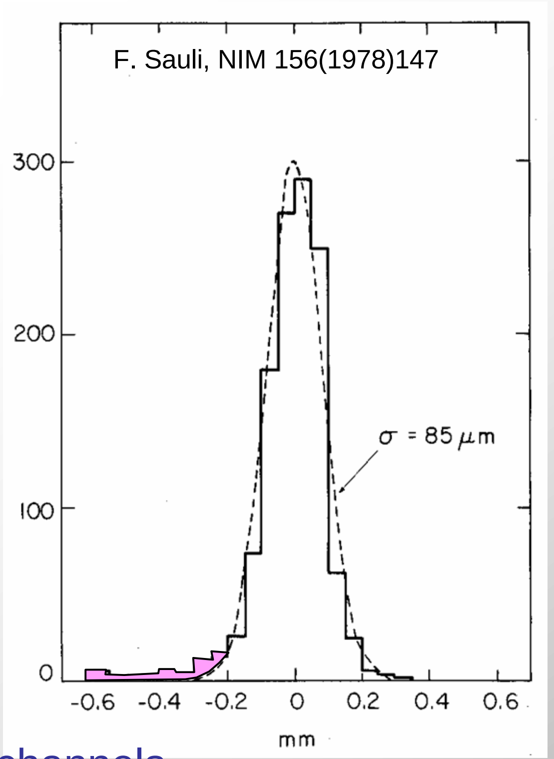
→ $N^2$ channels!



# Drift chambers

- Motivation: Building large MWPCs requires many wires → high mechanical stress. In addition resolution of MWPC is modest.
- New idea: Measure arrival time (= drift time) of electrons at sense wire relative to a time $t_0$.



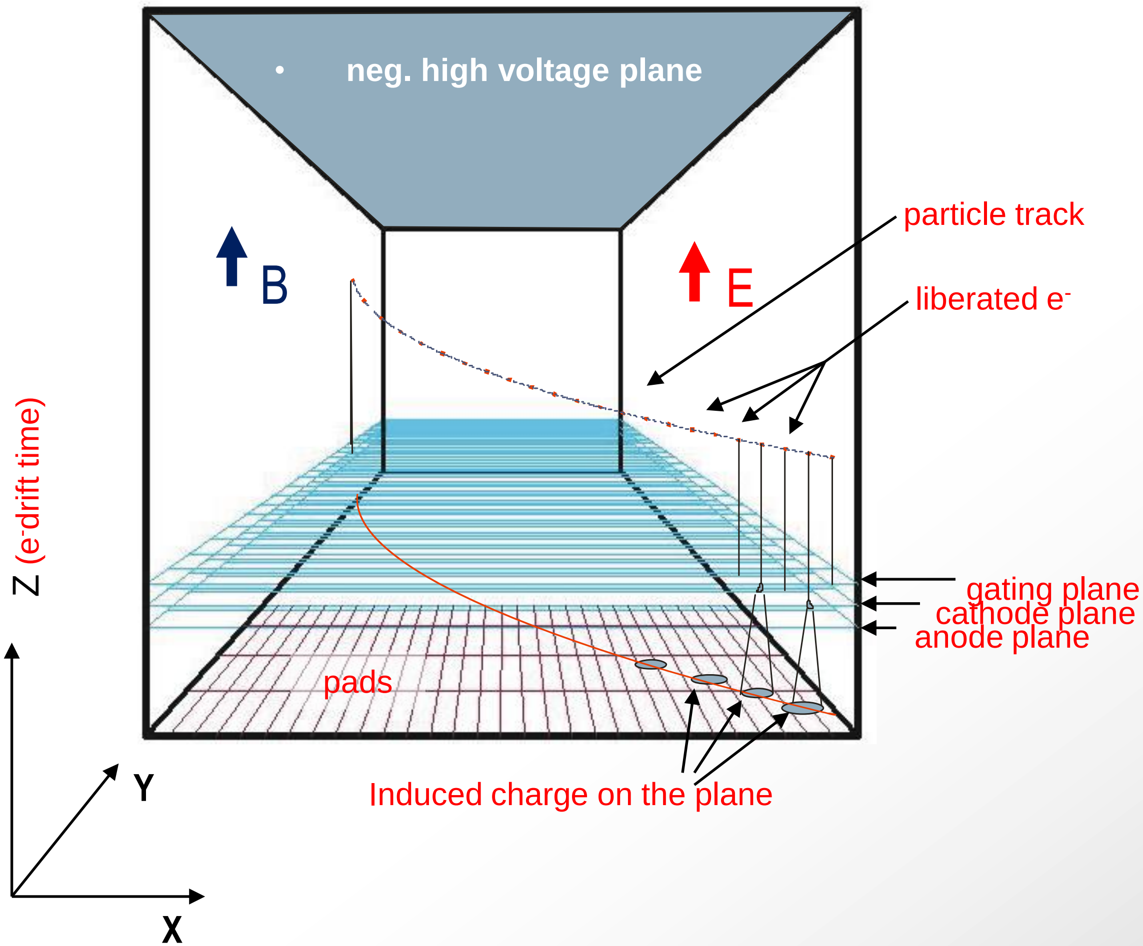




Advantages:

- smaller number of wires → less material, less electronics channels.
- Better resolution.

# TPC – Time Projection Chamber

(The ultimate gas detector)




full 3D track reconstruction:

- x-y from wires and segmented cathode of MWPC (or GEM)
- z from drift time

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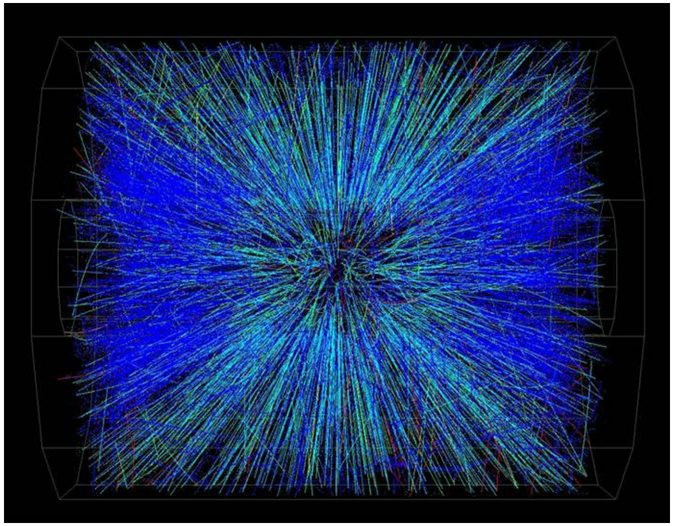
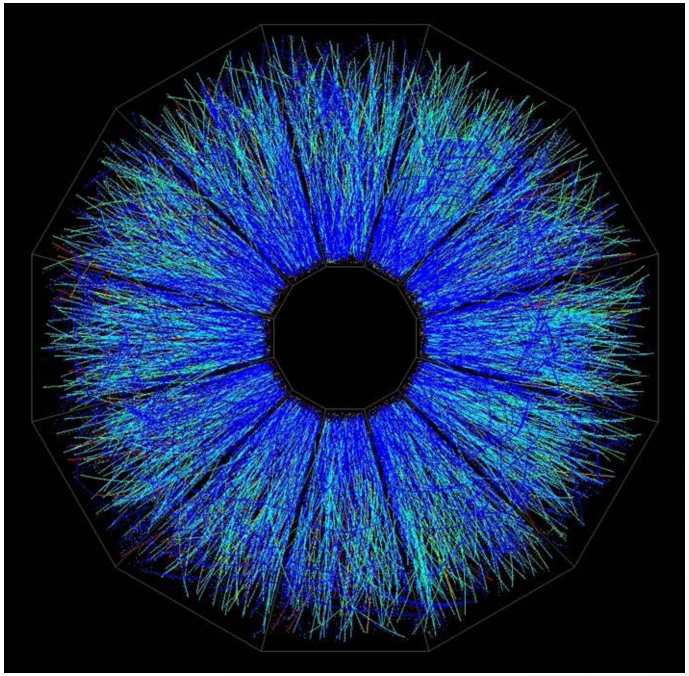
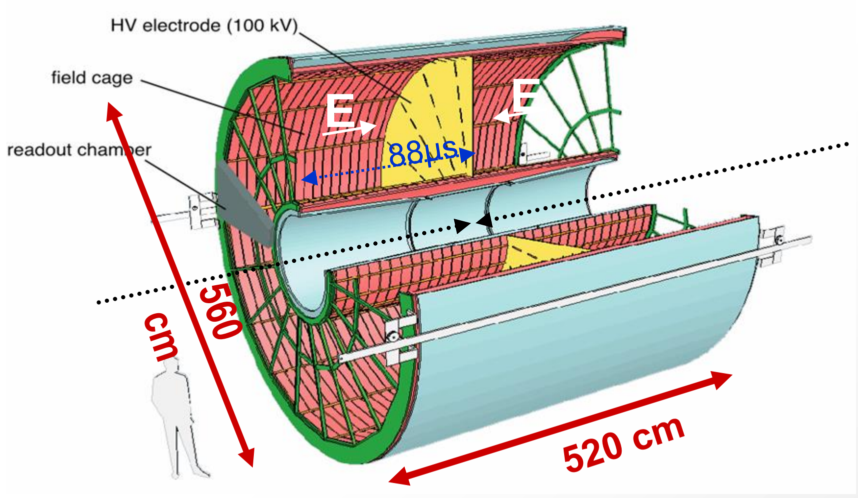
# TPC – Time Projection Chamber








Alice TPC

HV central electrode at –100 kV

Drift length 250 cm at E = 400 V/cm

Gas Ne-$CO_2$ 90-10

Space point resolution ~500 $\mu$m

dp/p = 2%@1GeV/c; 10%@10 GeV/c

Events from STAR TPC at RHIC

Au-Au collisions at CM energy of 130 GeV/n

Typically ~2000 tracks/event

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# Gas Detectors in LHC Experiments

ALICE: TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)

ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)

CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)

LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)

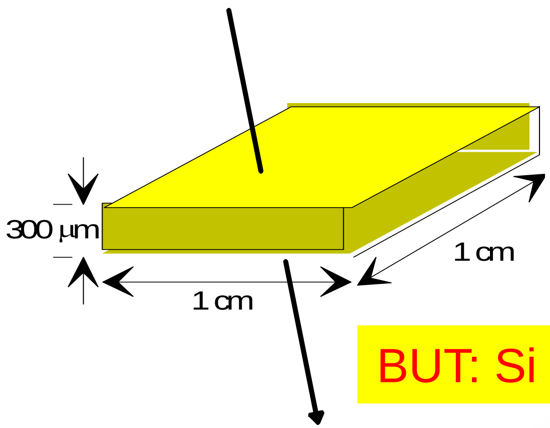
TOTEM: Tracker & trigger (CSC , GEM)

# Solid state detectors = Silicon detectors

We are looking for a detector to overcome some of the limitations of the gaseous detectors

- Small primary signal → need of gas amplification (not discussed: aging, rate limitations)
- Moderate spatial resolution (100 um)
- Massive frames, high voltage, gas circulation

**Silicon** (also GaAs, diamond) is very promising material



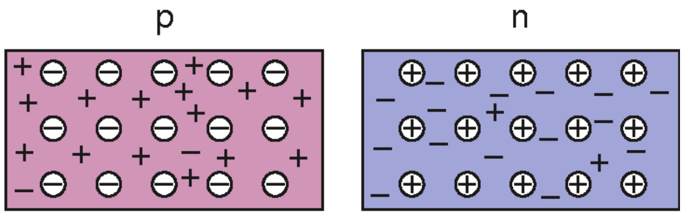

- ultra pure crystalline material
- $\rho_{Si} = 2.33$ g/cm$^3$
- Energy loss of particles in Si = 3.8 MeV/cm
- E(e-h pair) = 3.6 eV (≈ 20-30 eV for gas detectors)
- A particle traversing 300 μm of Si creates **~30'000** e/h pairs

BUT: Si is a semiconductor. It contains already free charge carriers.

At room temperature, in 1 x 1 x 0.03 cm$^3$, there are **$4.5 \cdot 10^8$** free charge carriers. We have to eliminate the free charges (= deplete the detector), such that our signal can be seen.

**→ Use the principle of the pn junction**

1. Dope Silicon with acceptor and donor atoms



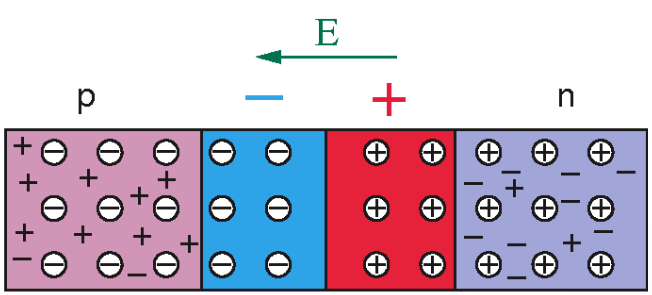

Boron: extra free holes

→ p-Si

Phosphor: extra free electrons

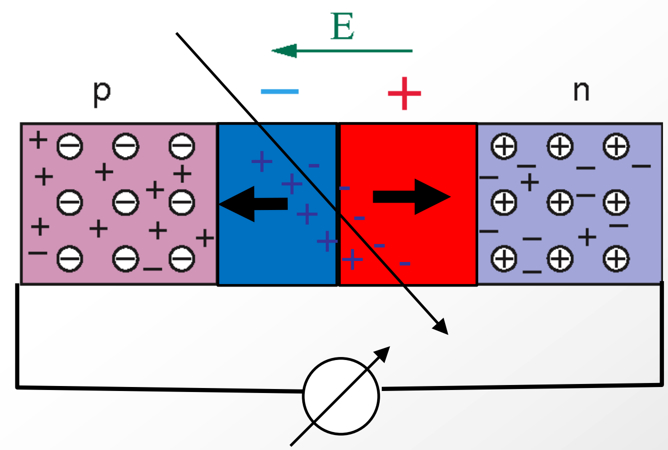
→ n-Si

2. Bring the two doped regions in contact

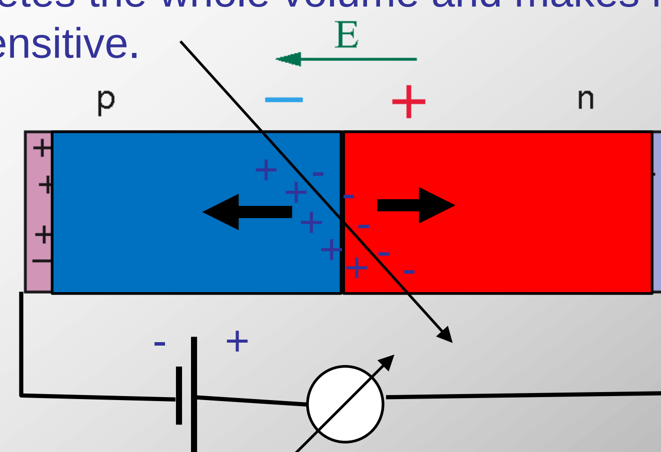



3. In the interface region holes and electrons will neutralise each other and create a depleted zone without any free charge carriers.

4. The resulting electric field separates newly created free charges → signal current

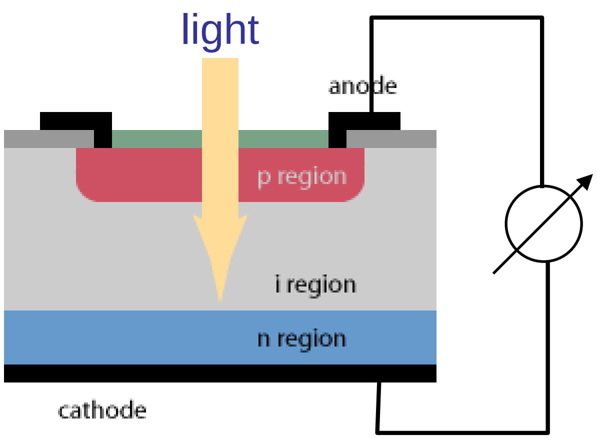



5. An external (reverse bias) voltage depletes the whole volume and makes it sensitive.

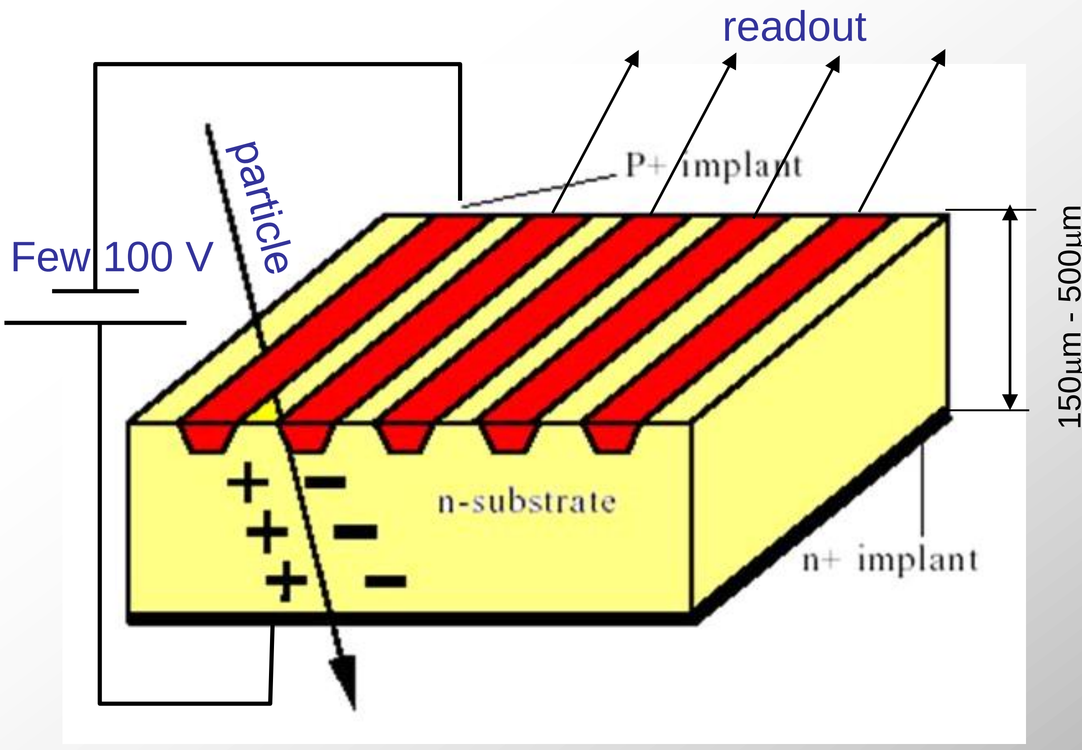


In the real world, Si-sensors are not produced by joining p and n doped material, but by implanting acceptors in a n-doped bulk (or donors in a p-doped bulk)

Simplest example: **(PIN) photodiode**



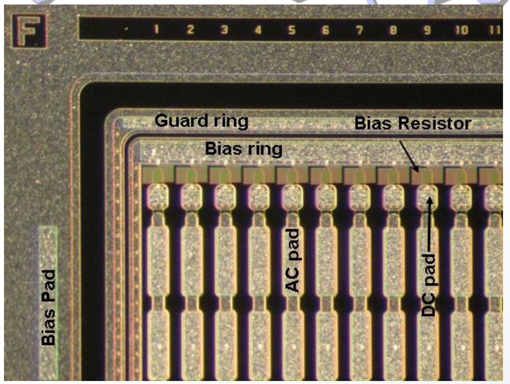

More complex: **Si microstrip detector**



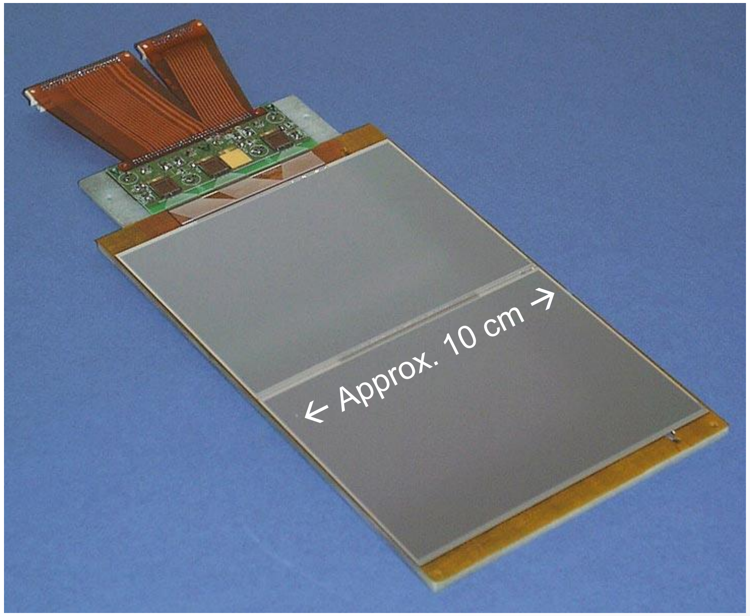
# Si microstrip detector

Highly segmented silicon detectors have been used in Particle Physics experiments for 30 years.

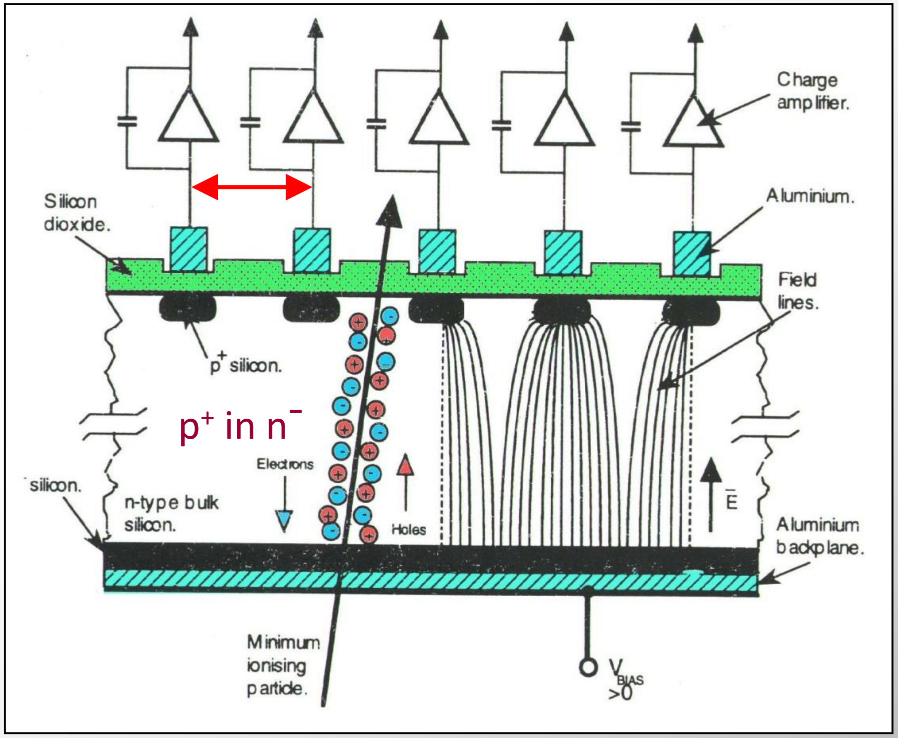
They are favourite choice for Tracker and Vertex detectors (high resolution, speed, low mass, relatively low cost)




A real detector with 2 sensors, pitch adaptor, readout electronics and flex cable




**Pitch ~ 50µm**




**Resolution ~ 5µm**

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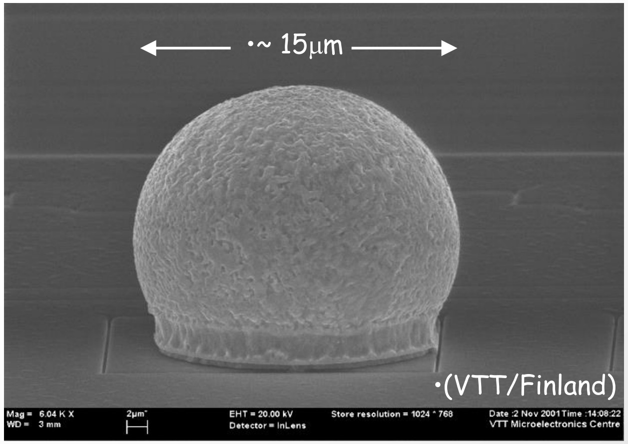
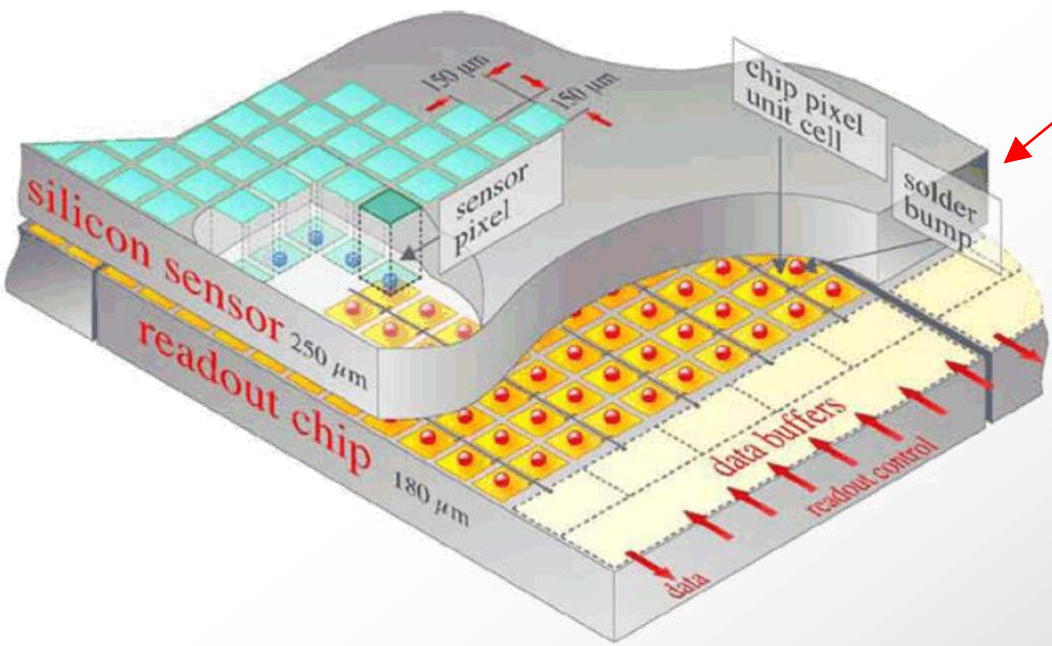
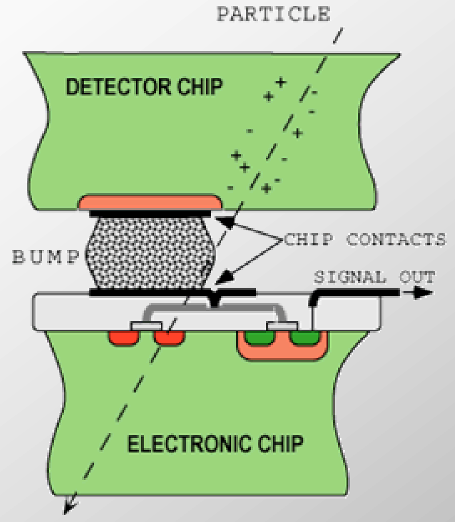
# Si pixel detector

- HAPS – Hybrid Active Pixel Sensor
- segment silicon to diode matrix with high granularity readout (⇒ true 2D, no reconstruction ambiguity)
- electronic with same geometry (every cell connected to its own processing electronics)
- connection by “bump bonding”
- requires sophisticated readout architecture
- Hybrid pixel detectors are/will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb

**Solder Bump: Pb-Sn**




**Flip-chip technique**

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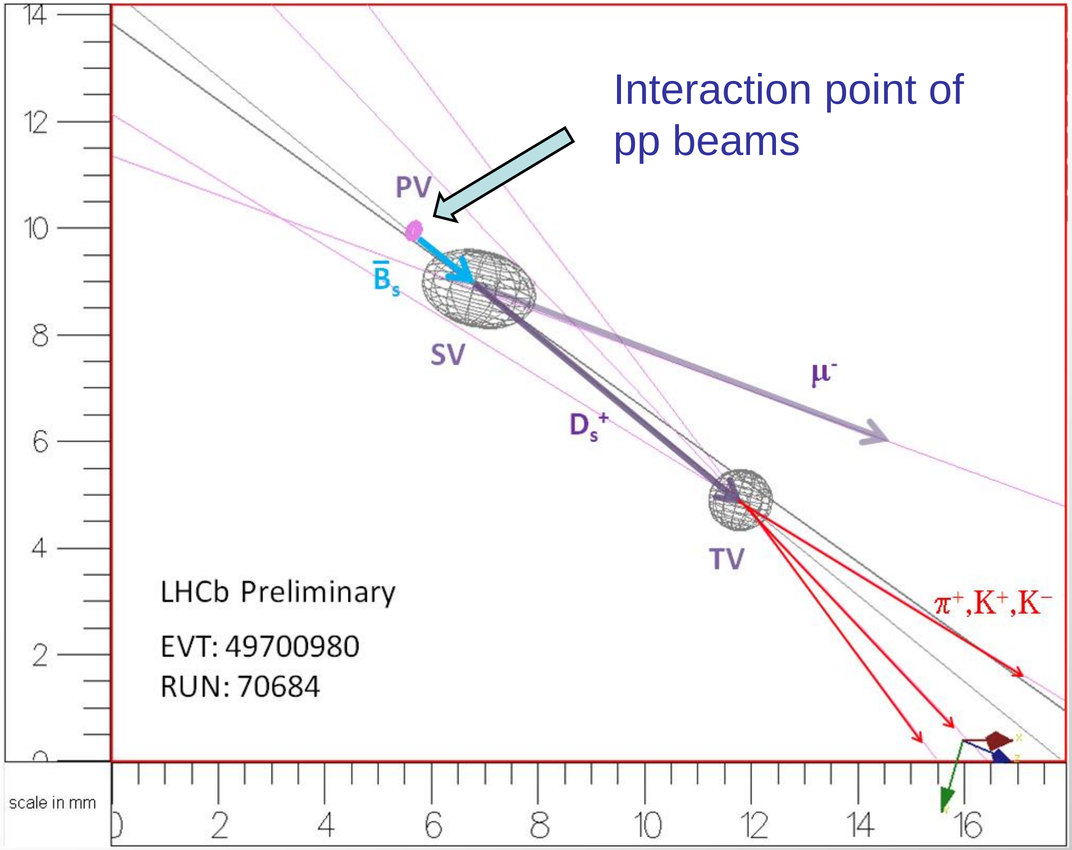
# Particle Identification via their lifetime

High resolution silicon detectors allow to observe secondary and tertiary vertices.

| PV | SV | TV |
|---|---|---|
| $pp \rightarrow x + \bar{B}_s$ | $\bar{B}_s \rightarrow D_s^+ + \mu^-$ | $D_s^+ \rightarrow \pi + K^+ + K^-$ |

$\tau_0(B_s) \approx 1.5$ ps

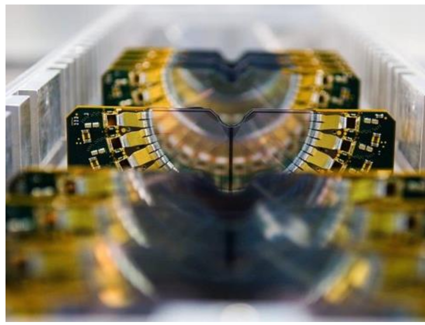
$\tau_0(D_s^+) \approx 0.4$ ps



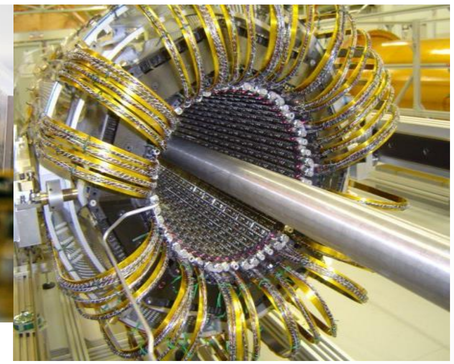
Silicon tracking detectors are used in all LHC experiments:

Different sensor technologies, designs, operating conditions,….

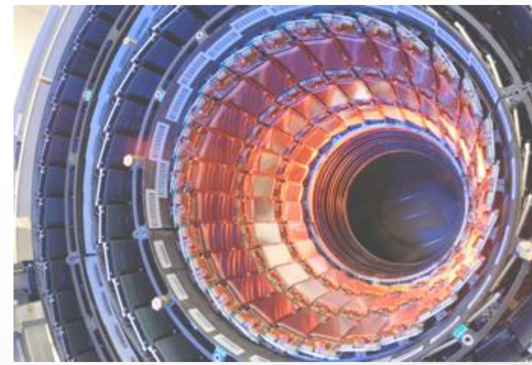
ALICE Pixel Detector



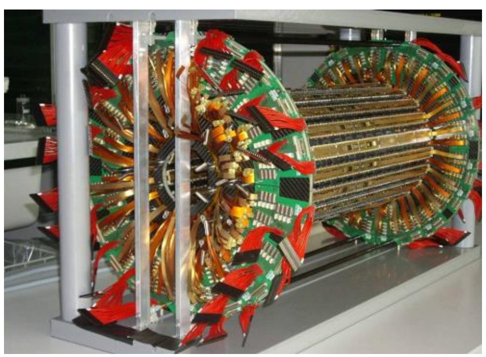
LHCb VELO



ATLAS Pixel Detector



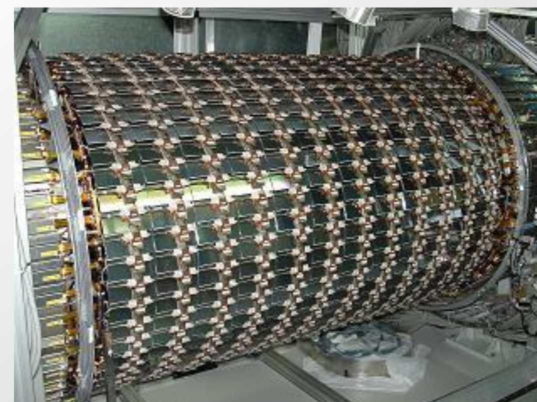
CMS Strip Tracker IB



CMS Pixel Detector

ALICE Drift Detector

ALICE Strip Detector



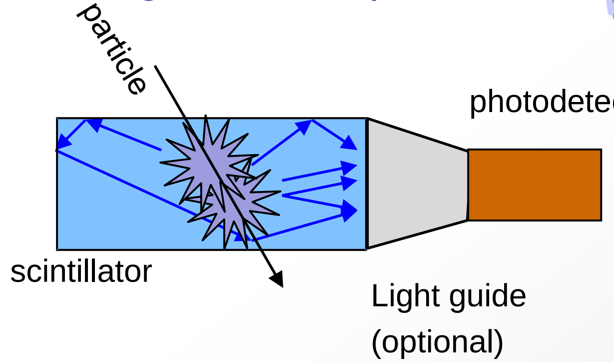
ATLAS SCT Barrel

•*P.Riedler, ECFA Workshop, Oct.2013*


Scintillation detectors

# Scintillation detectors

- Scintillators are materials which generate fluorescence light, when a particle or a high energy photon ($\gamma$) deposits energy in them.
- A scintillator alone is not yet a detector. We still have to collect and 'read' the scintillation light.




Two categories

**Organic scintillators**
(crystals, plastics or liquid solutions)

- Up to 10000 photons/MeV
- Low density $\rho$~1g/cm$^3$
- Relatively inexpensive (1 CHF/cm$^3$)

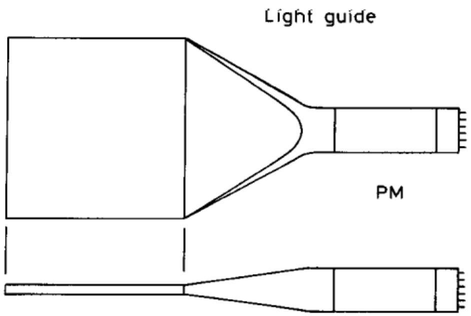

**Inorganic**
(crystalline structure)

- More light, up to 70000 ph/MeV
- higher density
- Quite expensive (100-1000 CHF/cm$^3$)

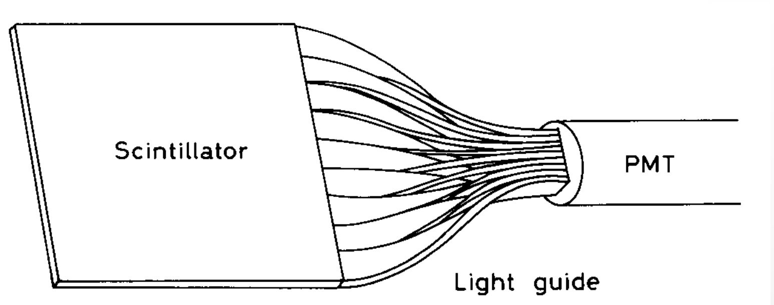

Don't confuse scintillators with lead glass ! Lead glass looks like a scintillator crystal, but it does not scintillate. Light is produced by Cherenkov effect.

# Plastic scintillators (organic)

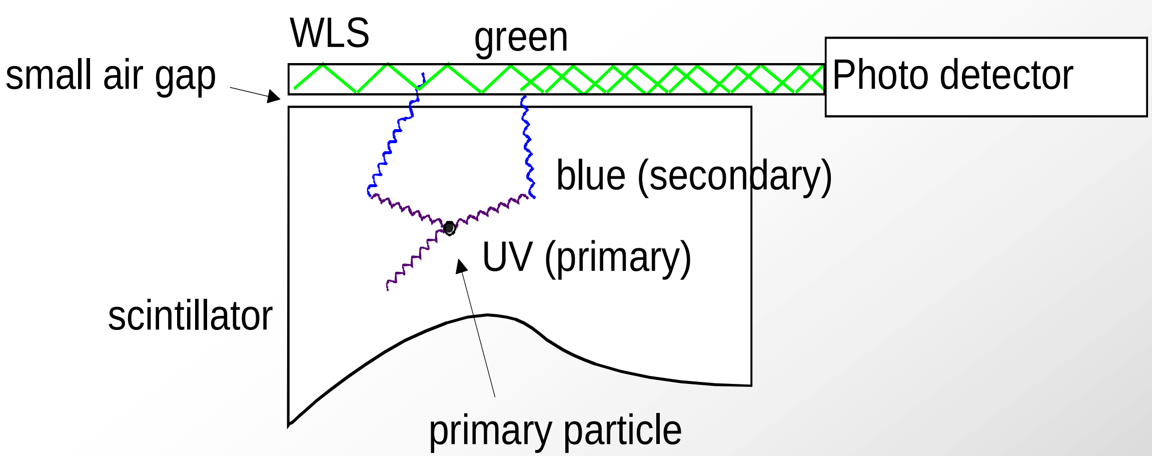
How to collect and read light from a large plastic plate ?




**“fish tail”**




**adiabatic**

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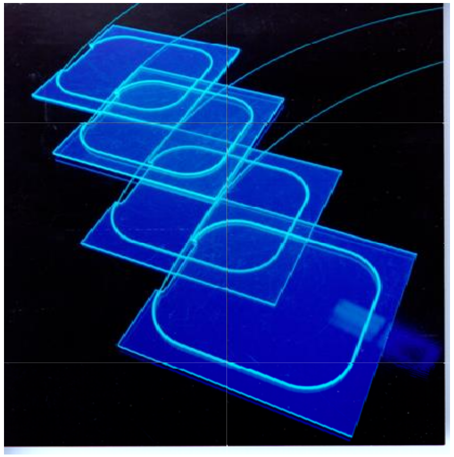
# Plastic scintillators (organic)

Poly Vinyl Toluene (PVT) or Poly Styrene (PS)

Plastic scintillators in various shapes (Saint Gobain)



Scintillating tiles of CMS HCAL.

Michigan University: ‘neutron wall’. The flat-sided glass tubes contain liquid scintillator.

Useful for large surface/volume, when no high spatial resolution is required

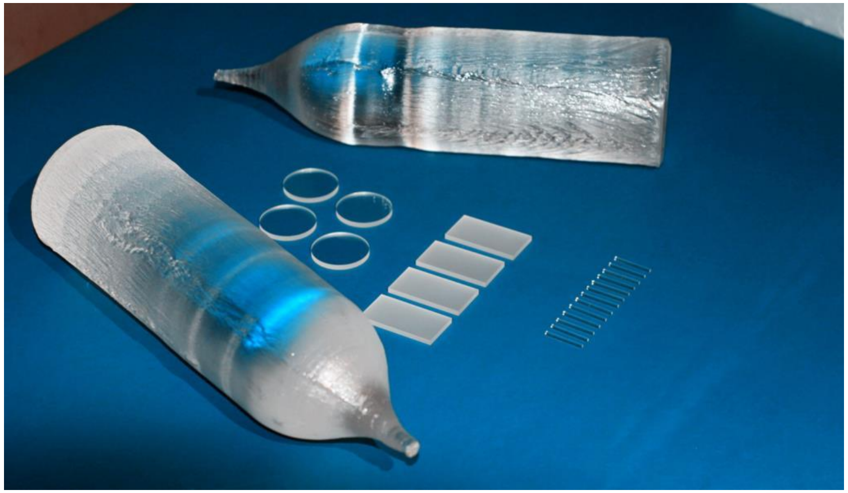
- Sampling calorimeters (HCAL in CMS, ATLAS, LHCb etc.),
- trigger counters (test beam)
- Time Of Flight (TOF) counters

Special application: Scintillating fibres → Fibre tracking

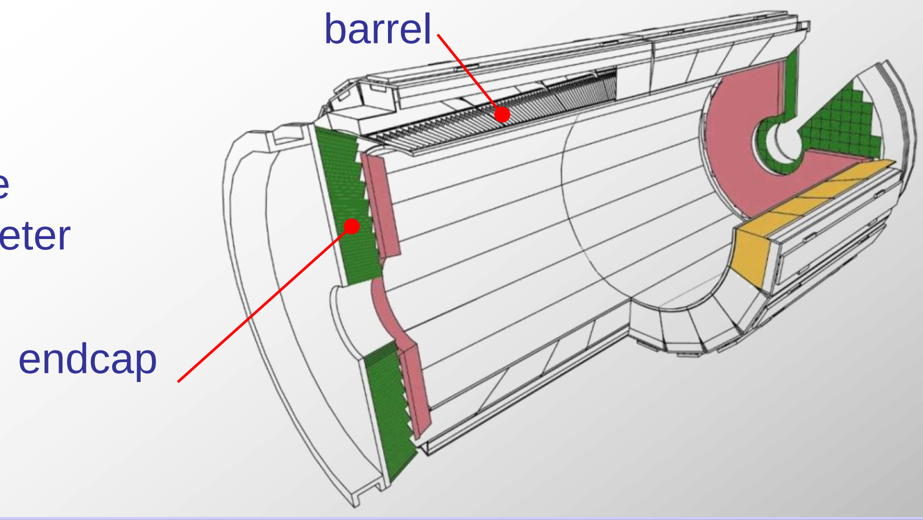
# Crystal scintillators  (inorganic)

Produced as (ideally) single crystalline ingots (e.g. by Czrochalski method)

Then cut and polished to the desired shape

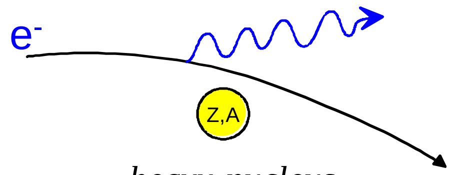


~75000 $PbWO_4$ crystals in the CMS electromagnetic calorimeter



At high energies, electrons ($e^{\pm}$) and photons have special ways to loose energy

- **Bremsstrahlung (BS)**

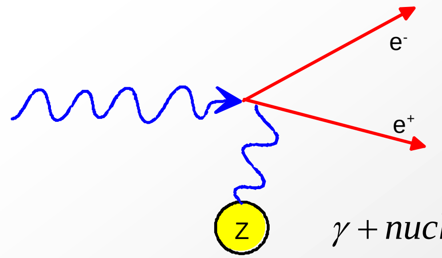



emission of a high energy photon (similar to synchrotron radiation)

Define Radiation Length $X_0$: distance after which an electron has lost 63% (1/e) of its energy by Bremsstrahlung.

Intensity of BS: ≈ $E/m^2$ → Only electrons produce BS. Muon and tau are too heavy.

- **Pair production (PP)**




$$\gamma + nucleus \rightarrow e^+e^- + nucleus$$

Define Pair Production Length $\lambda_{pair}$: distance after a photon produces an electron pair.

It turns out that $\lambda_{pair} = 9/7\ X_0$

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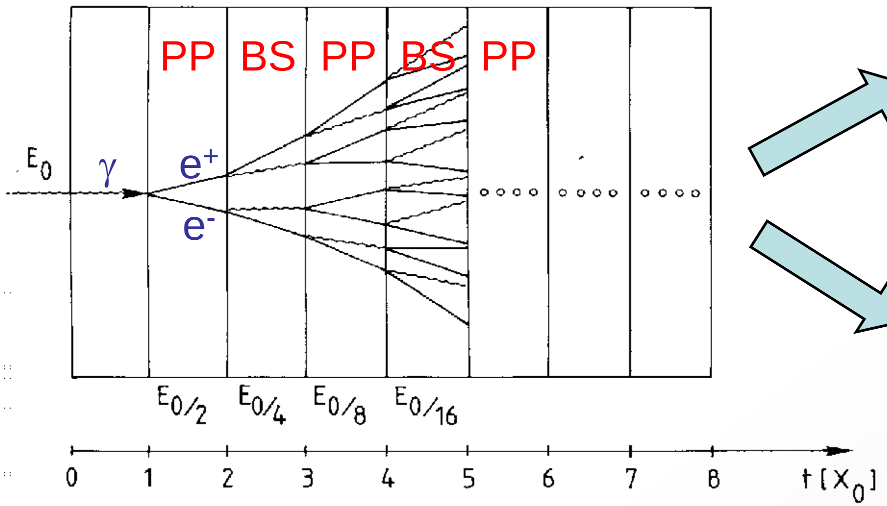
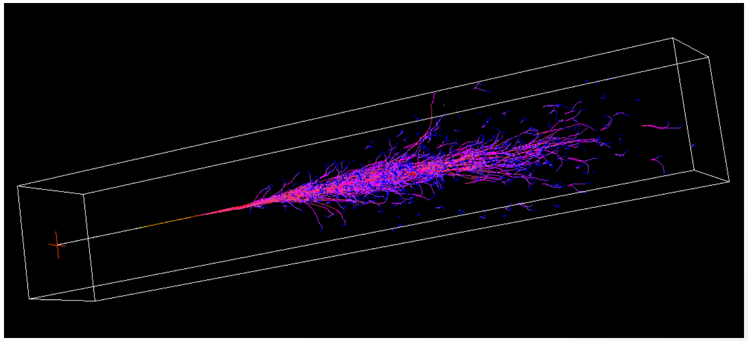
# Very short introduction to electromagnetic calorimetry

Simple model of an **electromagnetic cascade**

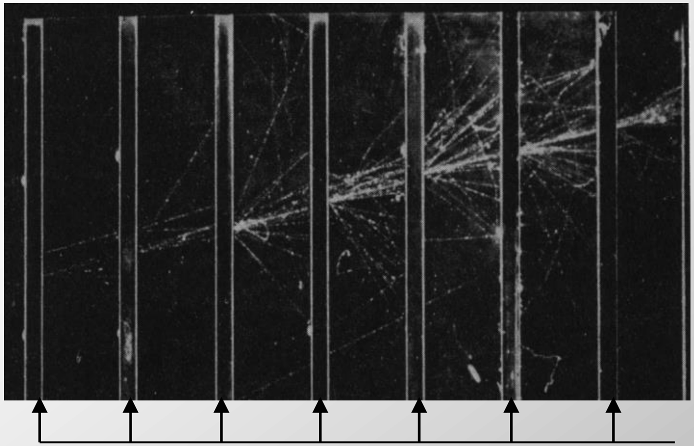



In an e.m. cascade the energy of **1** high energy electron/positron or photon is converted into **many** low energy e$^{\pm}$ and photons, all being stopped in the calorimeter → measurement of the total energy.

Homogeneous calorimeter, like CMS ECAL



Sampling calorimeter, like ATLAS ECAL



Pb plates

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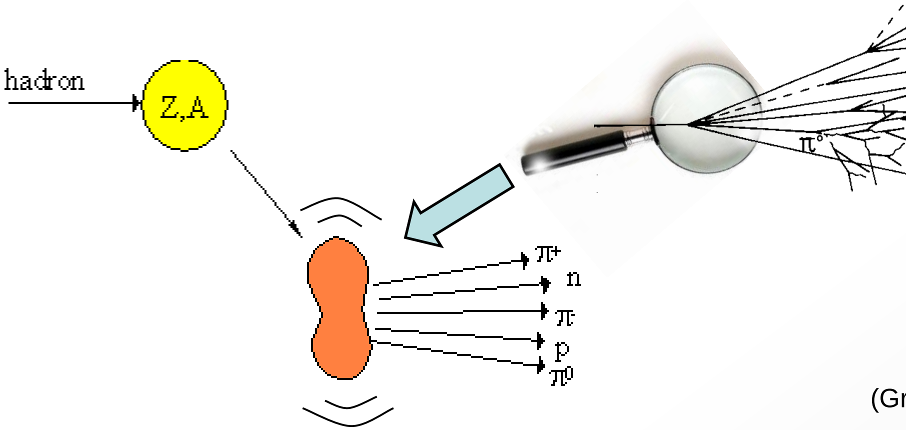
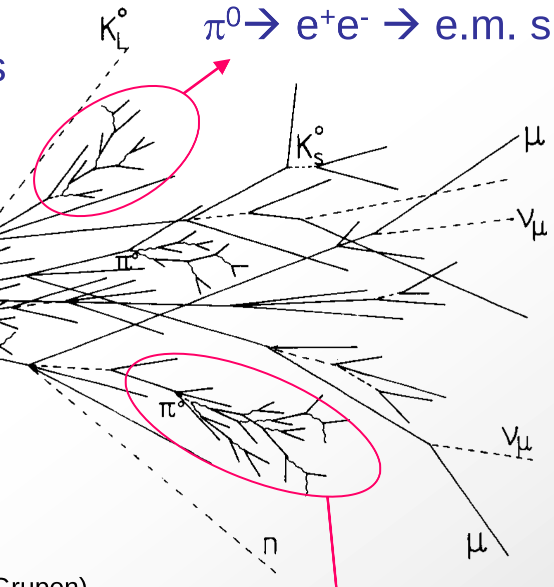
# Ultra short introduction to hadronic calorimetry

Also hadrons, e.g. p, k, $\pi$ and neutrons (!) can generate showers.

They are larger (longer) and involve lots of processes

$\pi^0 \rightarrow e^+e^- \rightarrow$ e.m. shower




(Grupen)

Nuclear spallation → radioactive fragments, neutrons

$\pi^0 \rightarrow e^+e^- \rightarrow$ e.m. shower

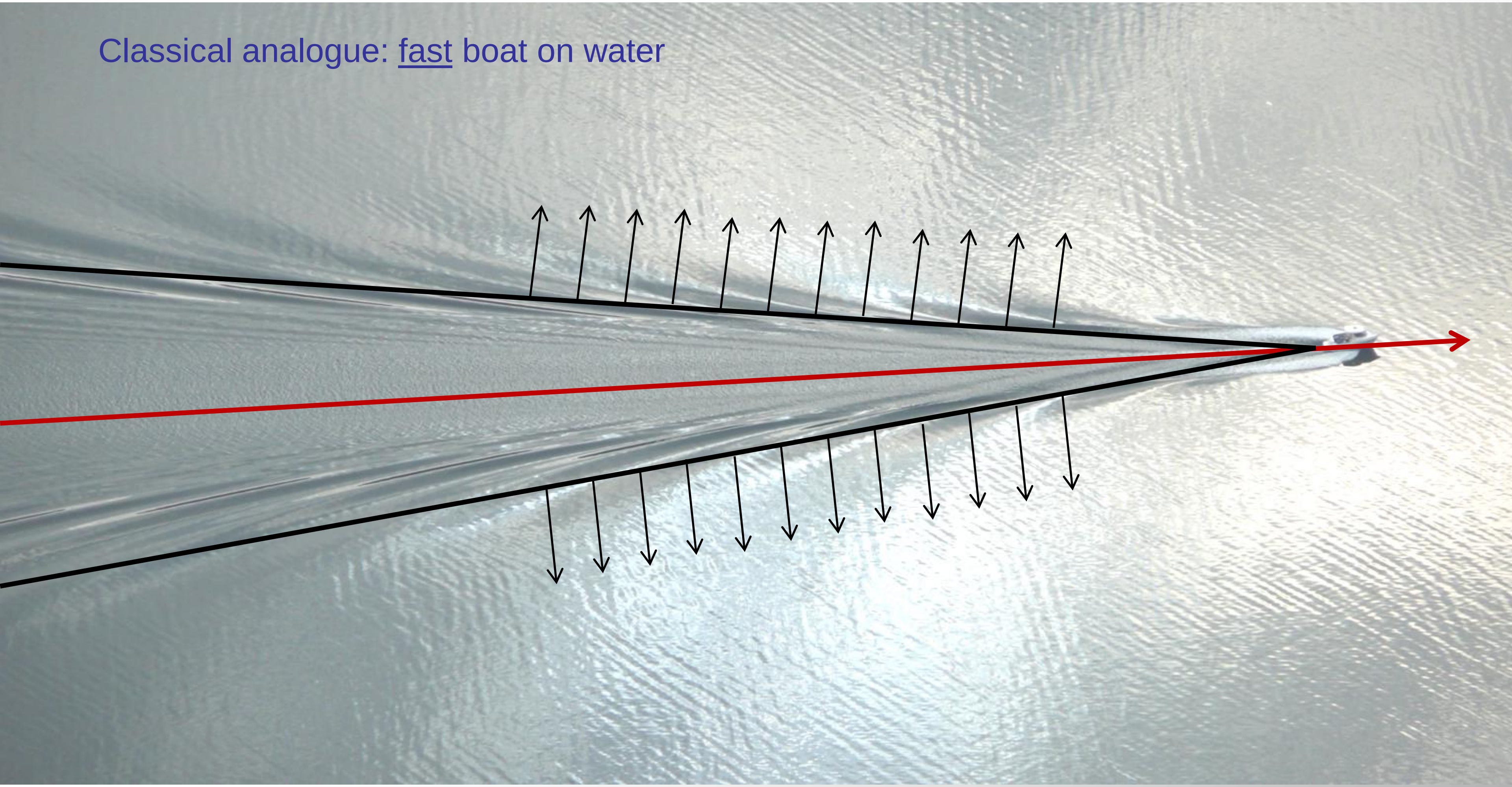
Hadronic calorimeters are larger (thicker) than electromagnetic ones. They measure the energy of neutrons and of hadronic jets (groups of close-by hadrons).


Cherenkov radiation

# Very short introduction to Cherenkov Radiation

A charged particle, moving though a medium at a speed which is greater than the speed of light in the medium, produces Cherenkov light.

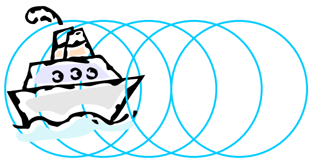
Classical analogue: fast boat on water



# Propagating waves

- A stationary boat bobbing up and down on a lake, producing waves

- Now the boat starts to move, but slower than the waves



No coherent wavefront is formed

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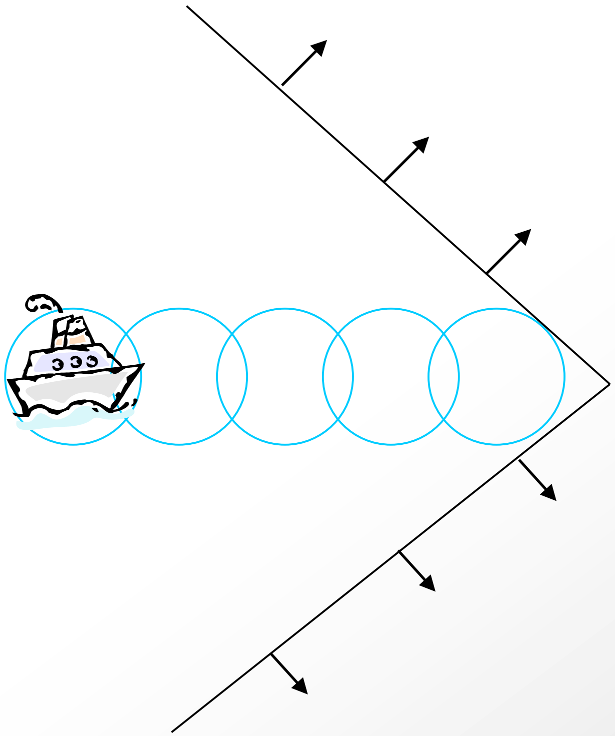
- Next the boat moves faster than the waves



A coherent wavefront is formed

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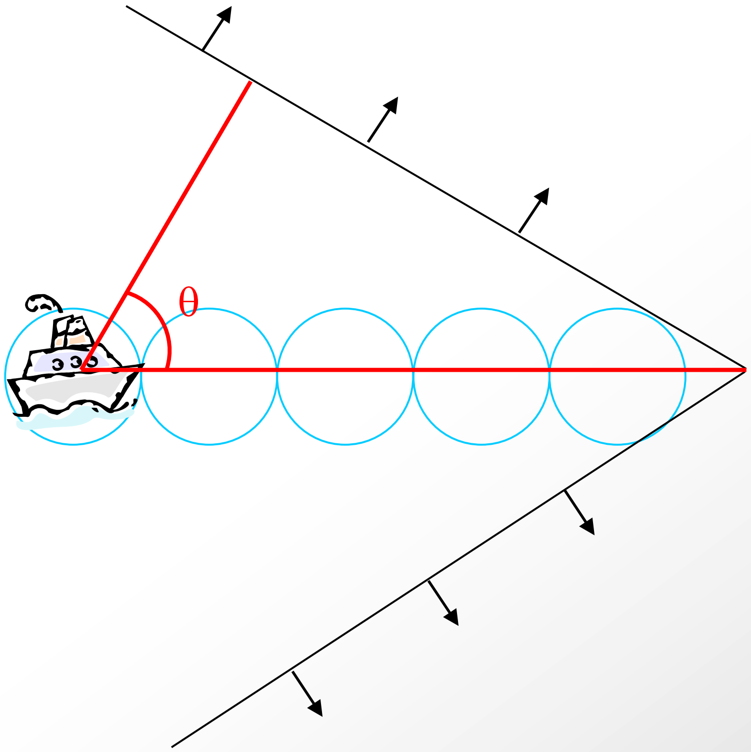
- Finally the boat moves even faster




The angle of the coherent wavefront changes with the speed

$$\cos\theta = v_{wave} / v_{boat}$$

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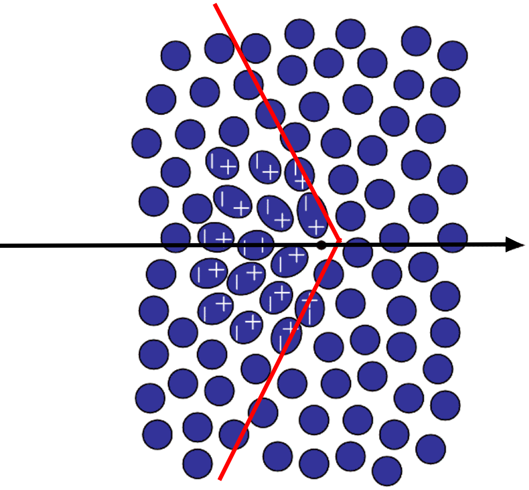
# … back to Cherenkov radiation



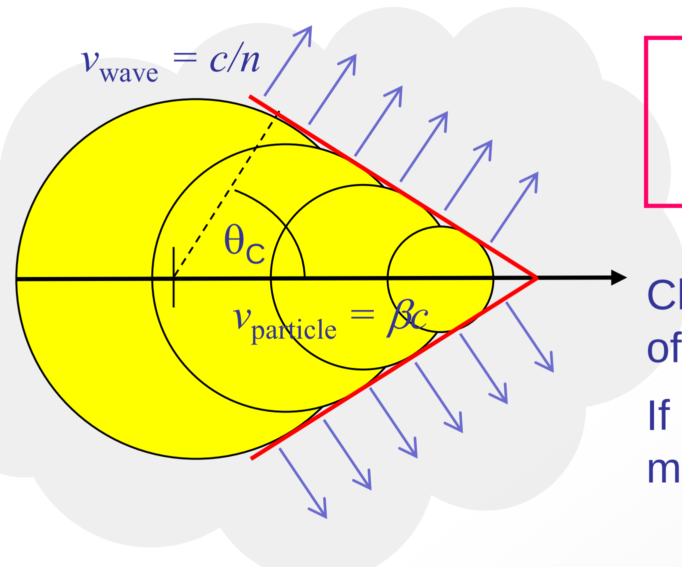
The dielectric medium is polarized by the passing charged particle.

↘ "the radiator"

A coherent light wave front forms if

$$v_{\text{particle}} \geq c_{\text{medium}} = \frac{c}{n}$$

$$\beta_{\text{particle}} = \frac{v}{c} \geq \frac{1}{n} \qquad (n = \text{refr. index})$$




$$\cos\theta_C = \frac{v_{\text{wave}}}{v_{\text{particle}}} = \frac{1}{n\beta}$$

Cherenkov radiation allows us to measure the speed ***v*** of a particle!

If we also know the momentum ***p***, we can calculate the mass of the particle

$$m = \frac{p}{v}$$

Mass known ➔ Particle identity known.

Used in LHCb, ALICE, COMPASS, …


Detector systems

# Detector Systems

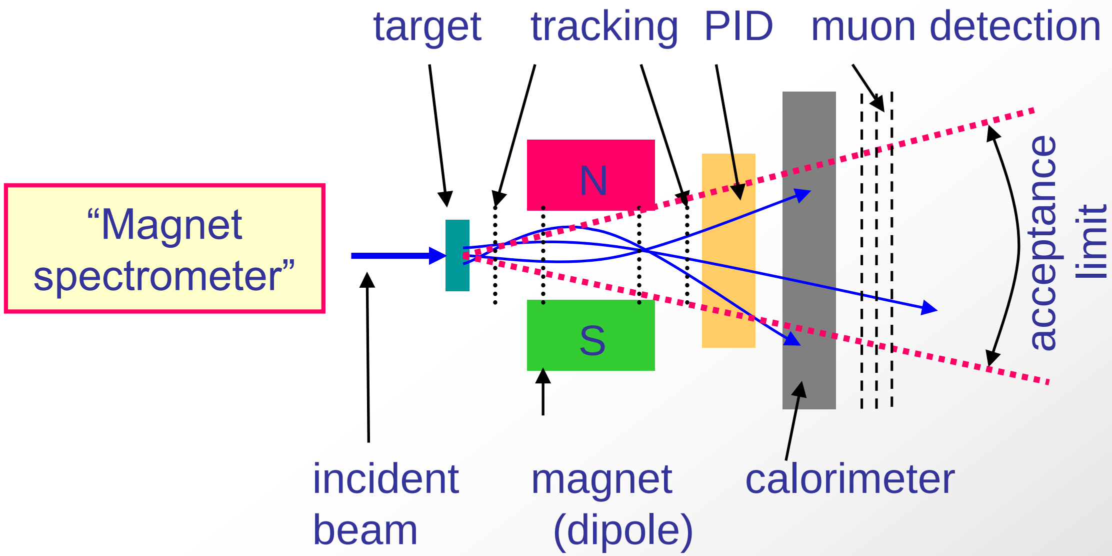
## What do we want to measure in a HEP experiment ?

- number of particles
- event topology
- momentum / energy
- particle identity
- jets
- missing energy/momentum

Can't be achieved with a single detector ! → integrate detectors to detector systems

## Geometrical concepts

Fixed target geometry




- Limited solid angle $d\Omega$ coverage
- rel. easy access (cables, maintenance)

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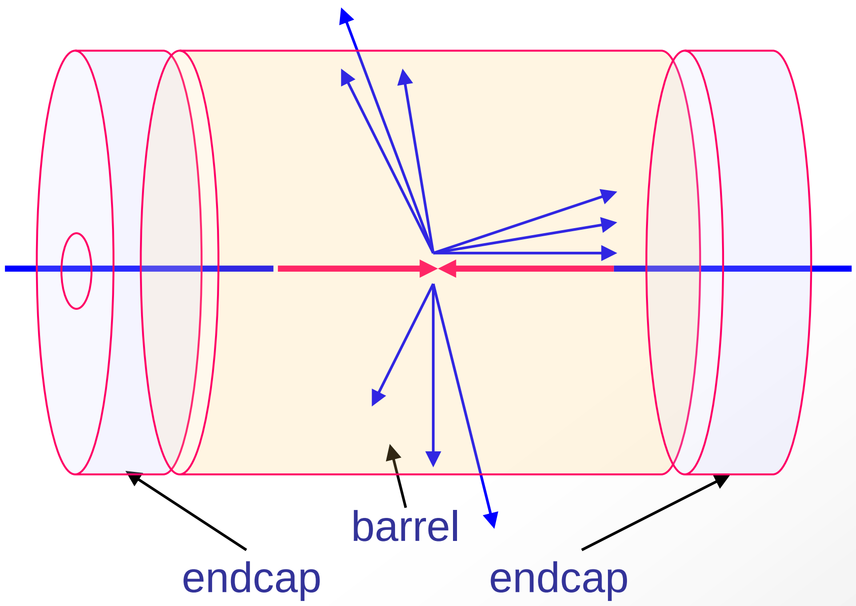
## Collider Geometry

"4π multi purpose detector"




- "full" dΩ coverage
- very restricted access
- barrel + endcaps

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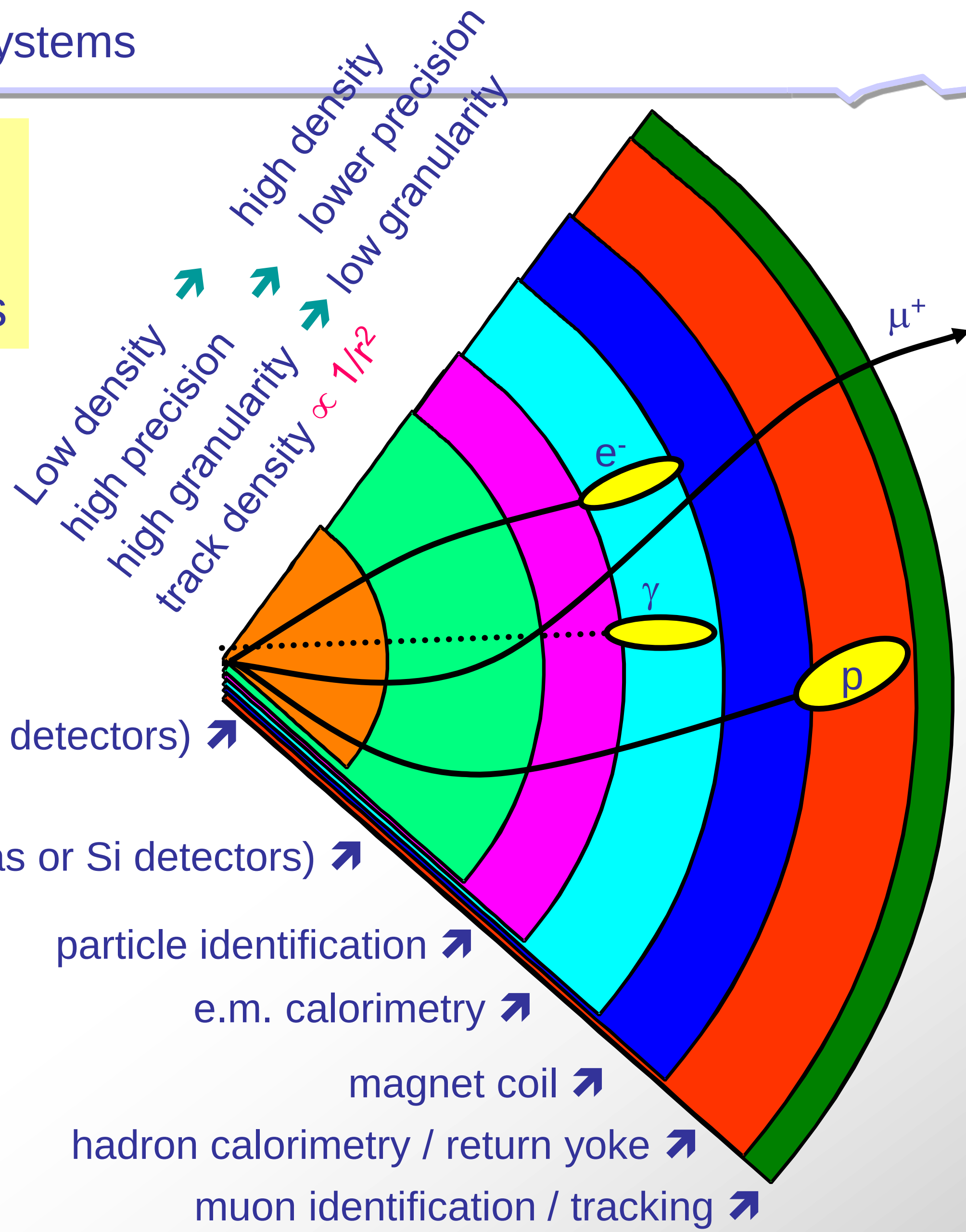
## Detector Systems

‘Typical’ arrangement of subdetectors




ATLAS and CMS require high precision tracking also for high energetic muons → large muon systems with high spatial resolution behind calorimeters.

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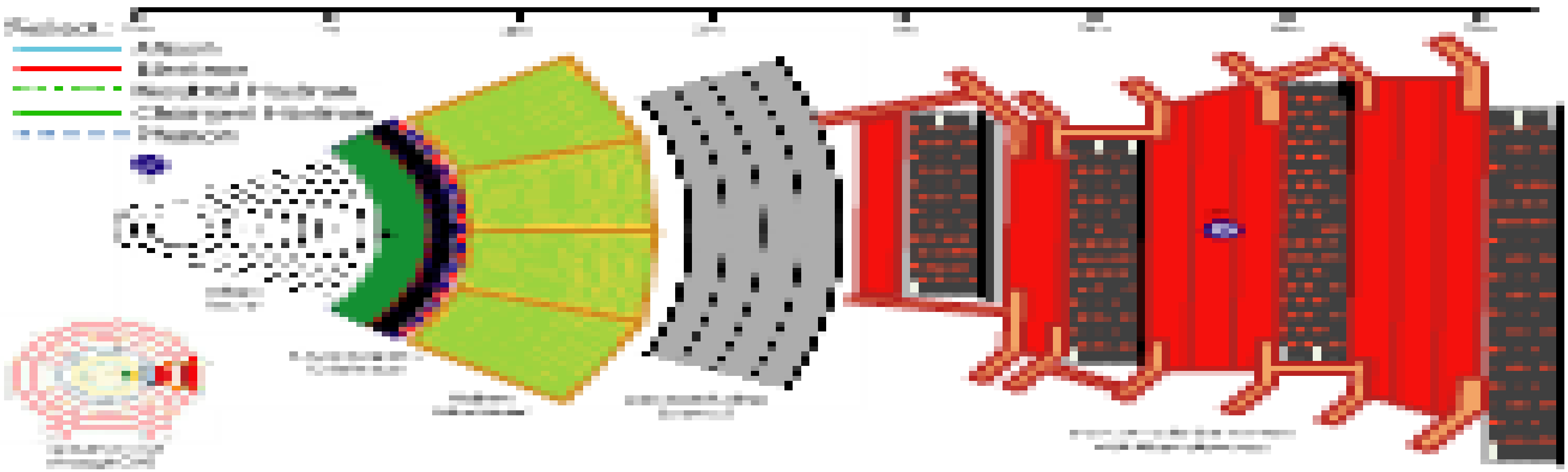
# A radial sector of a LHC experiment (CMS), animated



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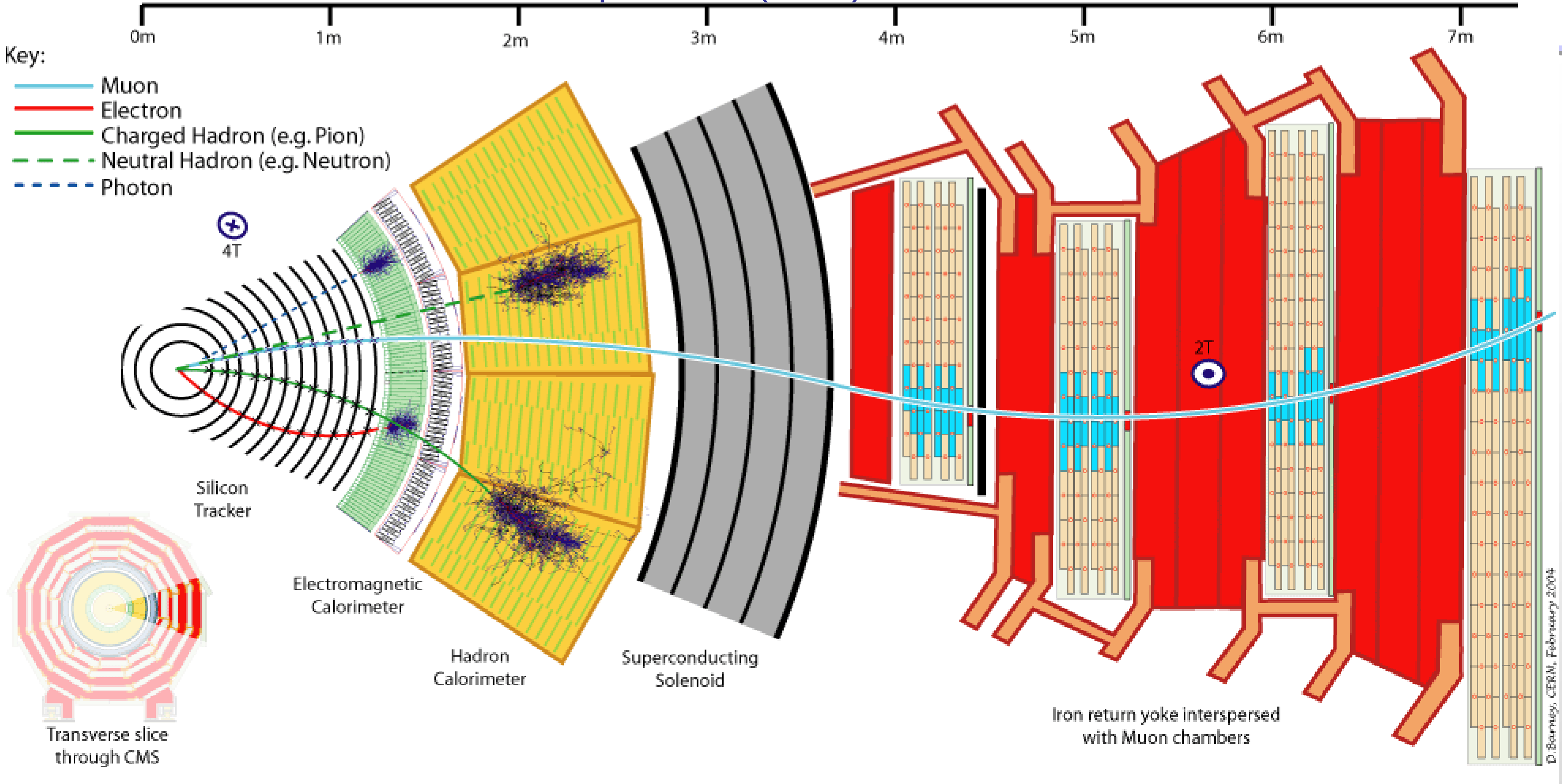
# A radial sector of a LHC experiment (CMS)




- Measurement of particle track space points with 10-50 μm precision
- Inner tracking systems in strong magnetic field (superconducting solenoid, B = 4T)
- Calorimeters, both electromagnetic and hadronic, inside magnet coil.
- High performance muon system. Many detector planes, magnetic field still high (2T).
- High requirements in terms of relative alignment and stability.

# Some practical considerations before building a detector

Find best compromises and clever solutions …

- Mechanical stability, precision ⇔ degradation of resolution (due to multiple scattering, conversion of gammas)
- Hermeticity ⇔ routing of cables and pipes
- Hermeticity ⇔ thermal stability (on-detector electronics can dissipate many kW of electrical power = heat).
- Hermeticity ⇔ accessibility, maintainability
- Compatibility with radiation
- … and always keep an eye on cost

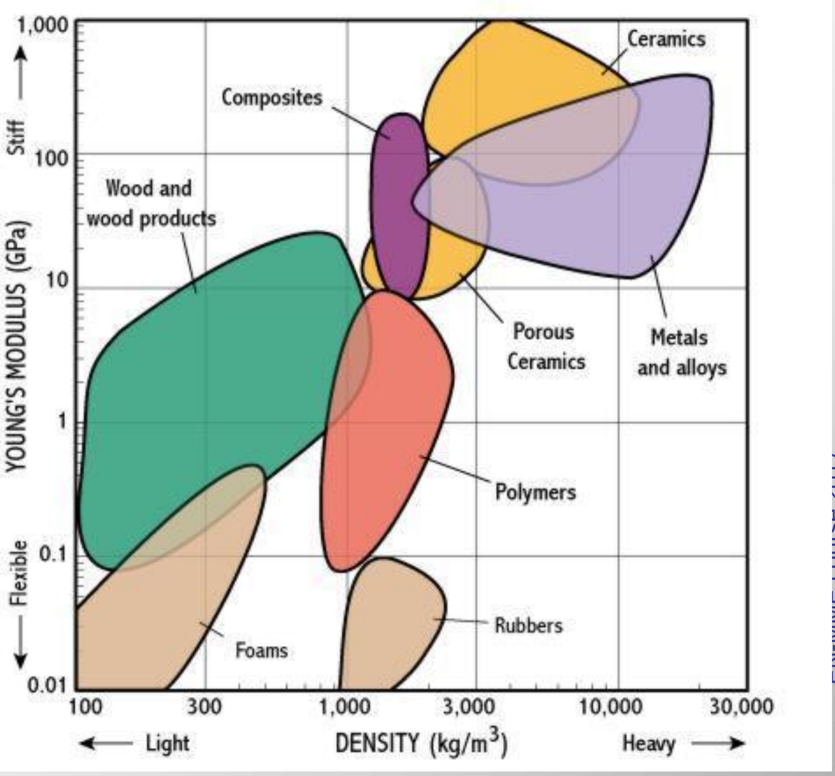
## Which materials to use ?

Many aspects to consider:

- 'strength' or more scientifically: Young's modulus

$$E\,[\mathrm{N/m^2}] = \frac{F/A}{\Delta L/L} \qquad \left(\text{Young's modulus} = \frac{\text{stress}}{\text{strain}}\right)$$

- specific density, or even better, radiation length
- safety related (flammability, chemical hazards, environmental effects
- electrical, magnetic, thermal properties
- cost

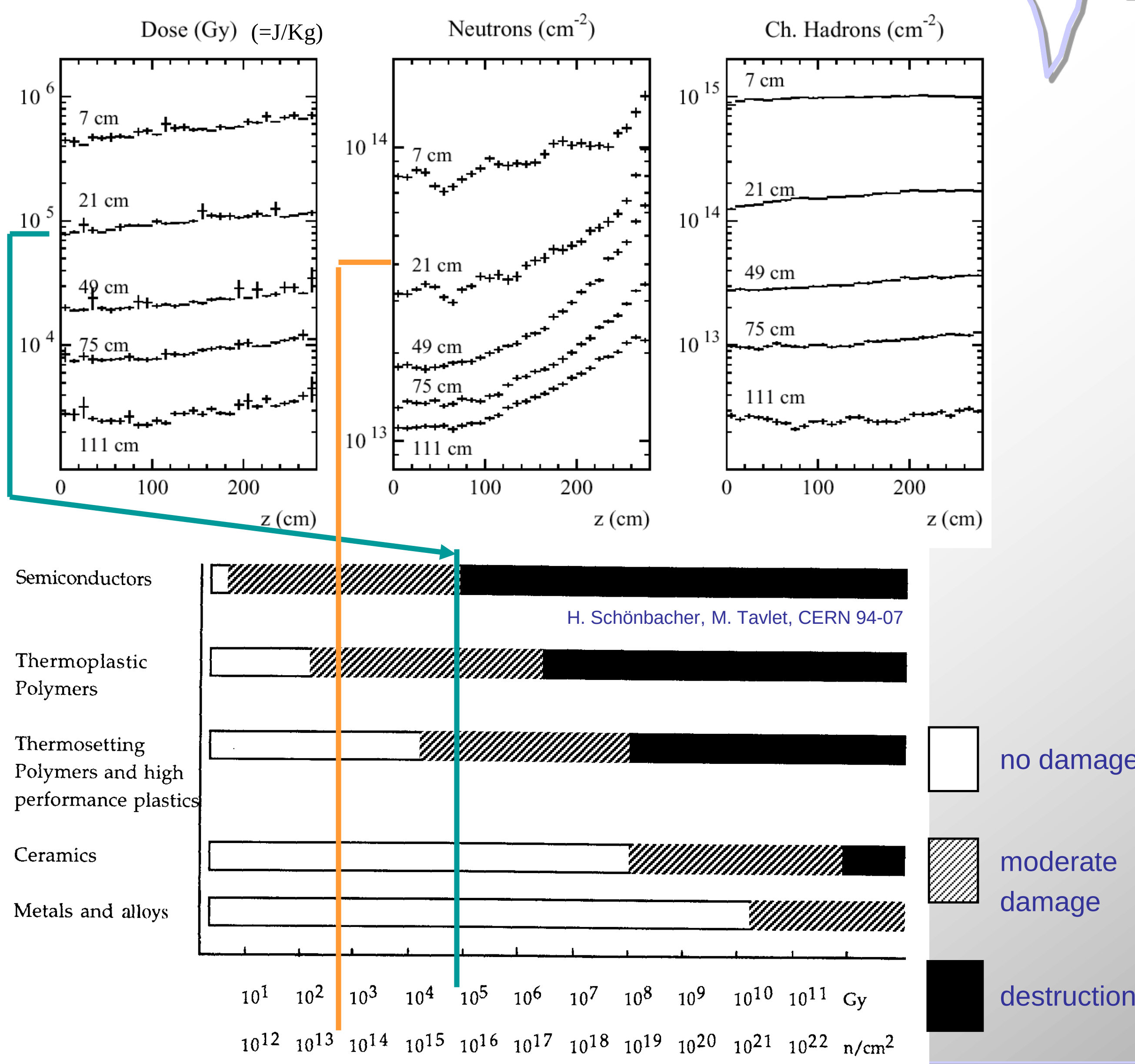



Composites, e.g. glass or carbon fiber reinforced epoxy materials, offer the possibility to produce light and stable constructions.

# Radiation damage to materials

Radiation levels in CMS Inner Tracker (0 < z < 280 cm)

Integrated dose / fluence over 10 years of operation.




H. Schönbacher, M. Tavlet, CERN 94-07

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# Summary and take-home messages

- Particles are detected through their interaction with matter
- In matter, particles **loose energy** and **scatter**

**Ionisation** and/or **excitation** of matter → detection

- A signal must be significantly larger than the noise of the amplifier (≈1000 $e^-$)
- Tracking: gas detectors (large surface, modest resolution) or silicon strip/pixel ('small' surface, high resolution)
- Calorimetry: energy measurement by creating a shower of particles in a massive block of material. Destructive!
  - Electromagnetic: scintillation crystals or sampling (e.g. LAr/Pb)
  - Hadronic: only sampling
- To obtain maximum information about all particles in one event, need to combine several different detectors to a detector system.
- Not covered here: the success and performance of a detector depends crucially on its electronics, data acquisition, performance simulation, engineering, …

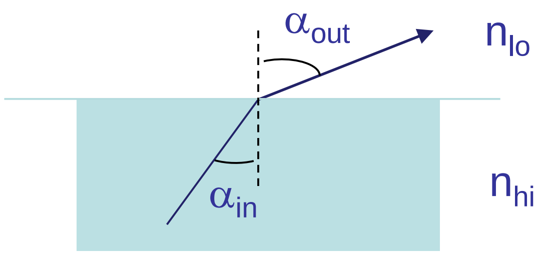

If there is time left …

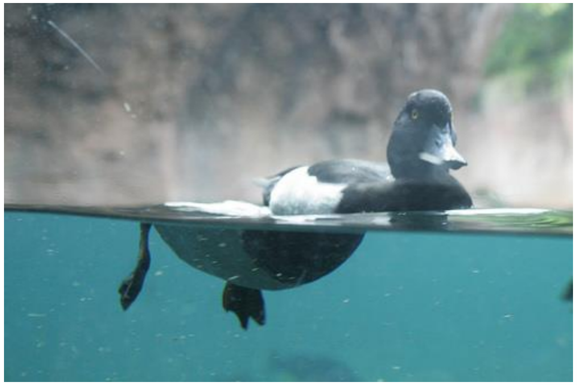
# Scintillating Fibres –
# Tracking Particles With (a little) Light

## The new Fibre Tracker for LHCb

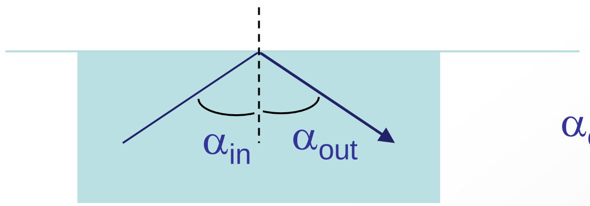
(My current project)

## Refraction



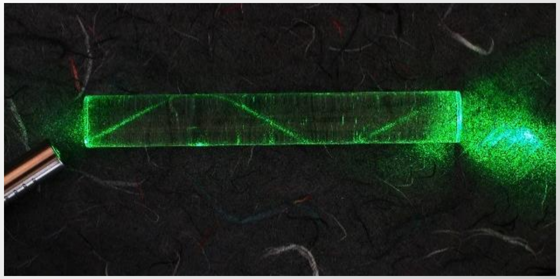



## Total internal reflection



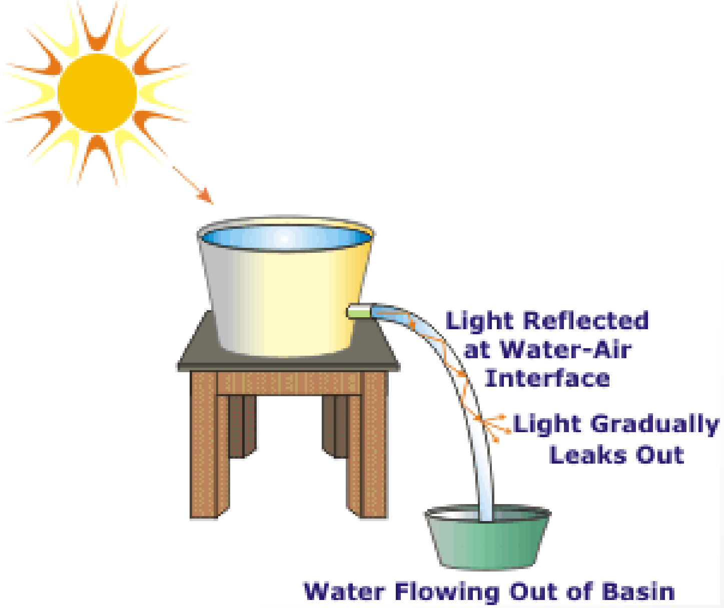

$\alpha_{crit} = \mathrm{asin}(n_{lo}/n_{hi})$

$\alpha_{in} > \alpha_{crit} \rightarrow \quad \alpha_{out} = \alpha_{in} \quad R = 100\%$



Jean-Daniel Colladon, a 38-year-old Swiss professor at **University of Geneva**, demonstrated (by accident) light guiding or **total internal reflection** for the first time in **1841.**

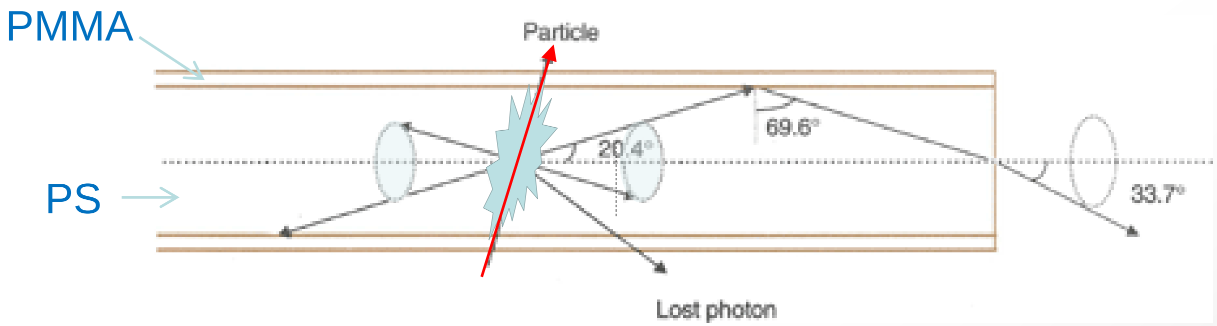
He had actually studied law (!) and worked on speed of sound in water and water jets.




# Basics of scintillating fibres (remember organic scintillators)

Scintillating fibre = Polystyrene (PS) core + plexiglass (PMMA) cladding

n ~ 1.59 n ~ 1.49




$$\theta_{crit} = \operatorname{asin}\left(\frac{1.49}{1.59}\right) = 69.6°$$

$$\varepsilon_{trap} \geq \frac{1}{4\pi}\int_0^{20.4°} 2\pi\, sin\theta d\theta$$

Trapping fraction

$$\approx 3.1\%$$

(per side)

There are fibres with a special double cladding which achieve 5.4% (per side)

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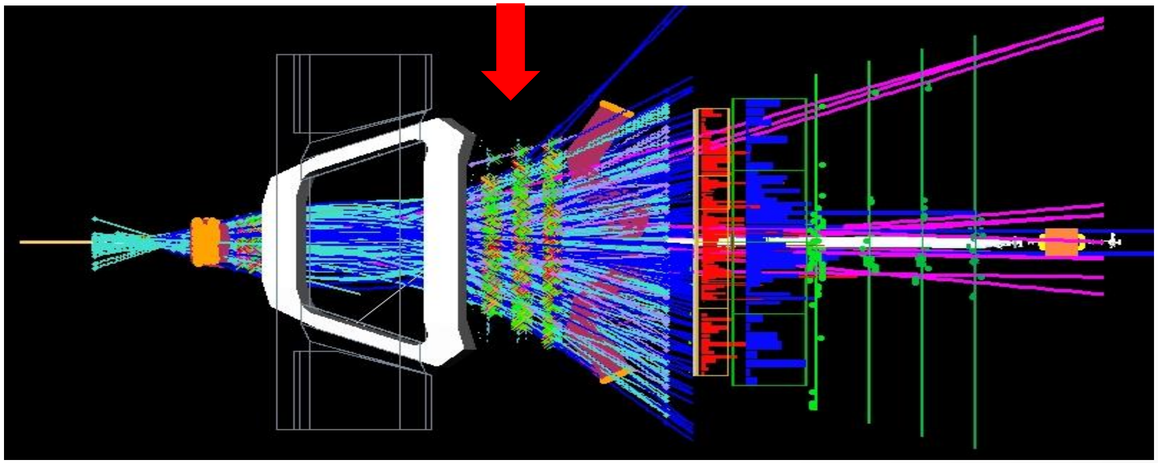
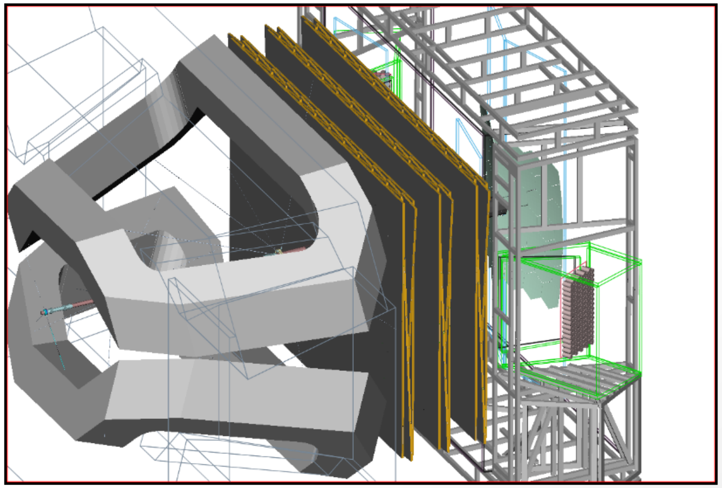
LHCb is building a large SciFi tracker for coordinate and angle measurements after the magnet

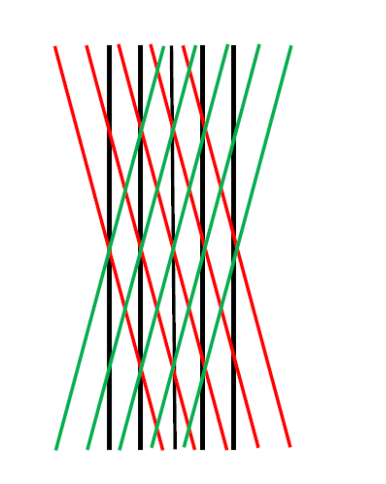
Future location of our SciFi tracker in LHCb



- Requirements:
- $\sigma_x$ < 100µm (bending plane)
- Low mass, 1% $X_0$ per layer
- Readout every 25 ns
- Radiation tolerant up to 35 kGy and $10^{12}$ n/cm$^2$



3 stations with 4 planes each (stereo angle ±5º)



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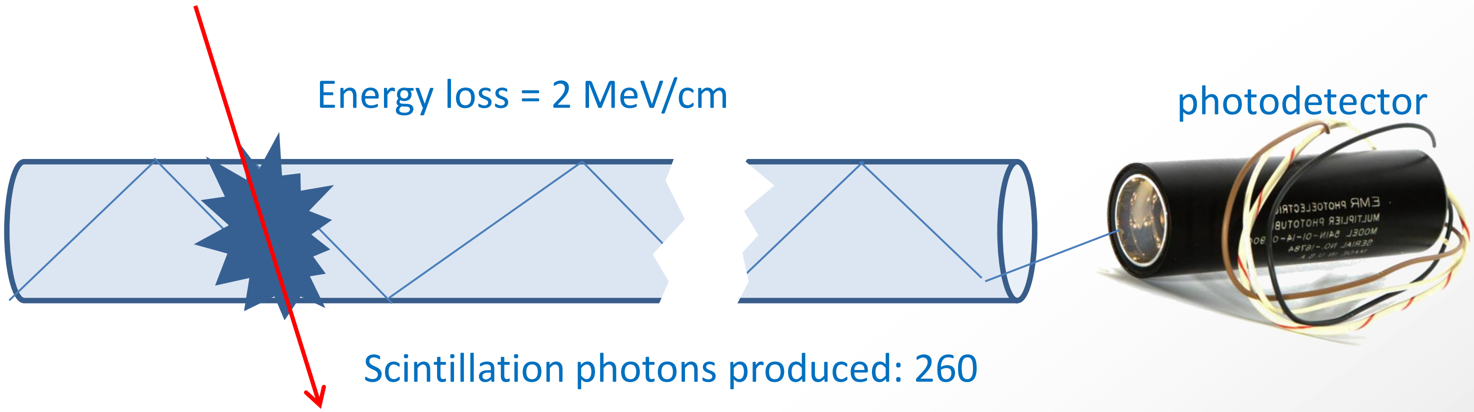
## Challenge

100 μm resolution can only be achieved with very thin fibres. We decided to use Ø250 μm.

How much light does such a fibre produce when a particle passes through?




- Scintillation yield: $dY_\gamma/dE$ = 8000 ph / MeV → $Y_\gamma = 260$
- Trapping inside fibre (1 hemisphere): 5.4% → $Y_\gamma \sim 13$
- Attenuation losses over 2 m: 50% → $Y_\gamma \sim 7$
- Efficiency of photodetector (typ. PMT): 20% → $Y_{p.e.} \sim 1$

A VERY small signal!

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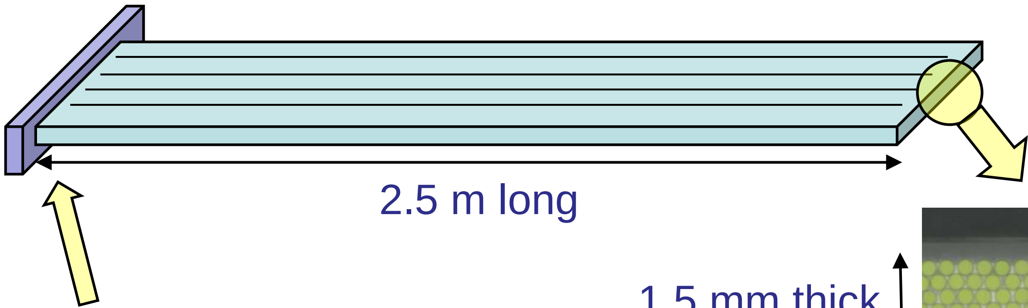
## Solutions

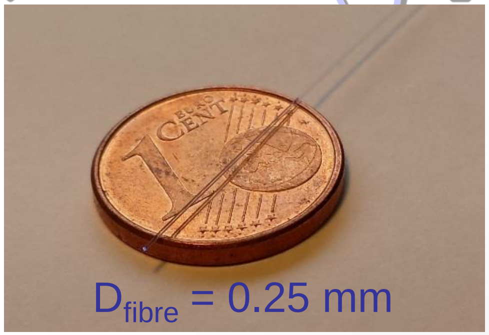
1) Produce multi-layer fibre mats instead of individual fibres

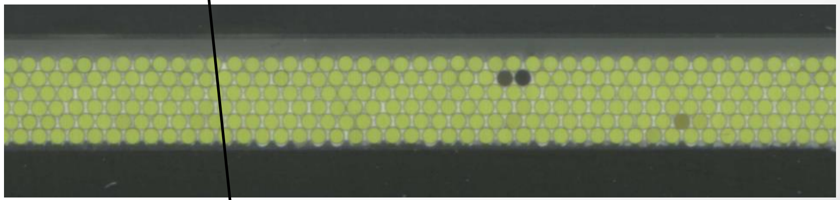


2.5 m long

2) put a mirror at the other end

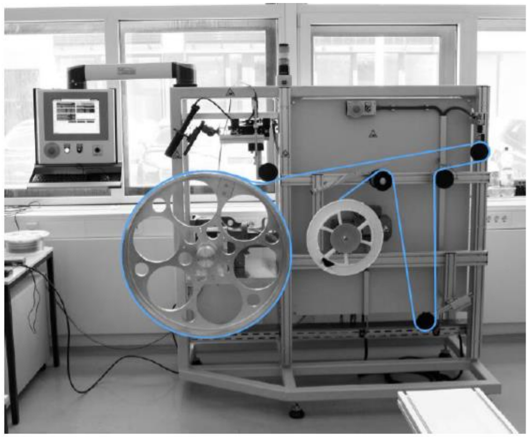
1.5 mm thick



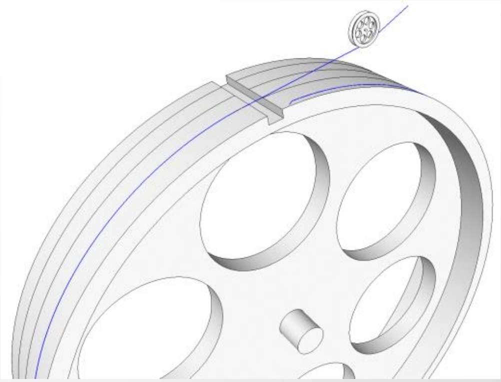



6 layers + epoxy glue

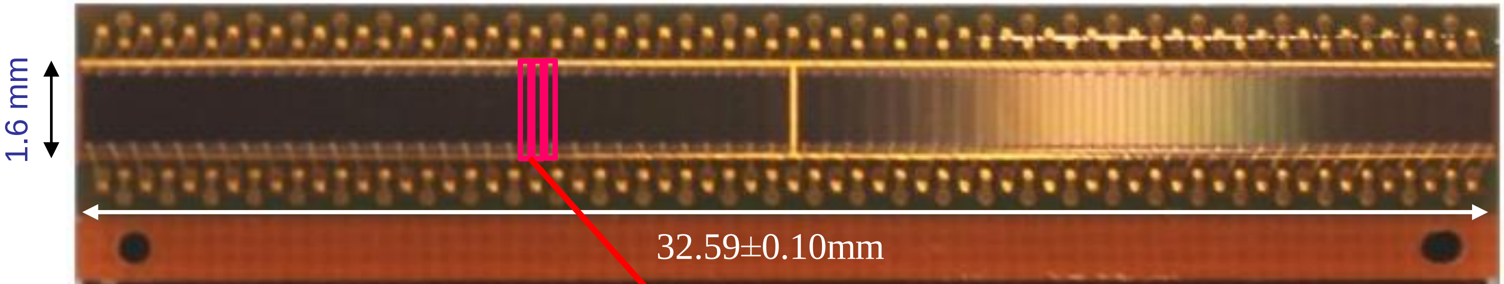
Ø80 cm wheel with fine thread (p=0.275 mm)



Machine for fibre mat winding



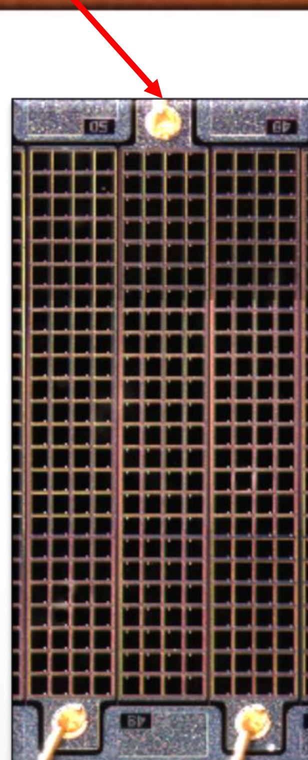
## 3) Replace Photomultiplier by SiPM Array (Silicon photomultiplier)

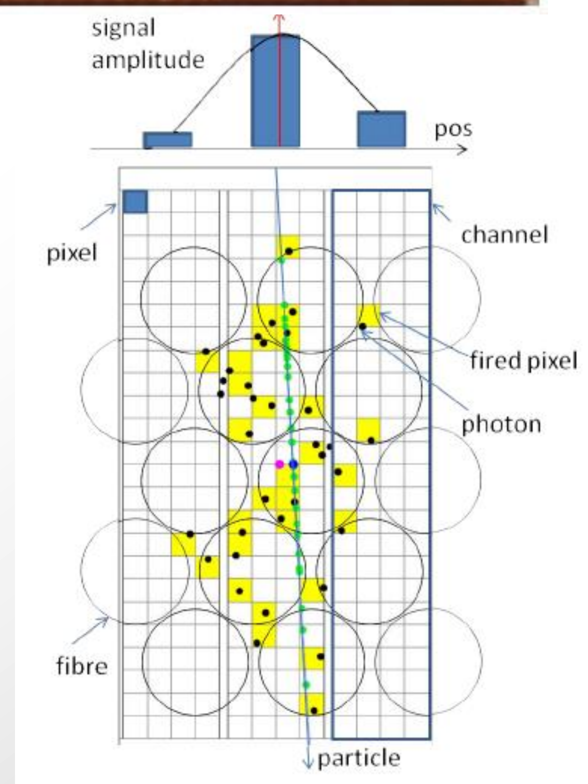



128 channels

= super fast and super sensitive Digital camera

- 40 M pictures / s
- Single photon sensitive, efficiency approx. 50%



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# Status

- We ordered 11’000 km of scintillating fibres (>8000 km already delivered an tested)
- 500 fibre mats produced (1100 needed)
- 5500 SiPM arrays ordered
- Start to assemble the detector at point 8 (LHCb) from March 2018 onwards
- Install detector in LHCb end of 2019
- Physics from 2021 on.