



# Particle Physics I

## Lecture 3: Particle detection

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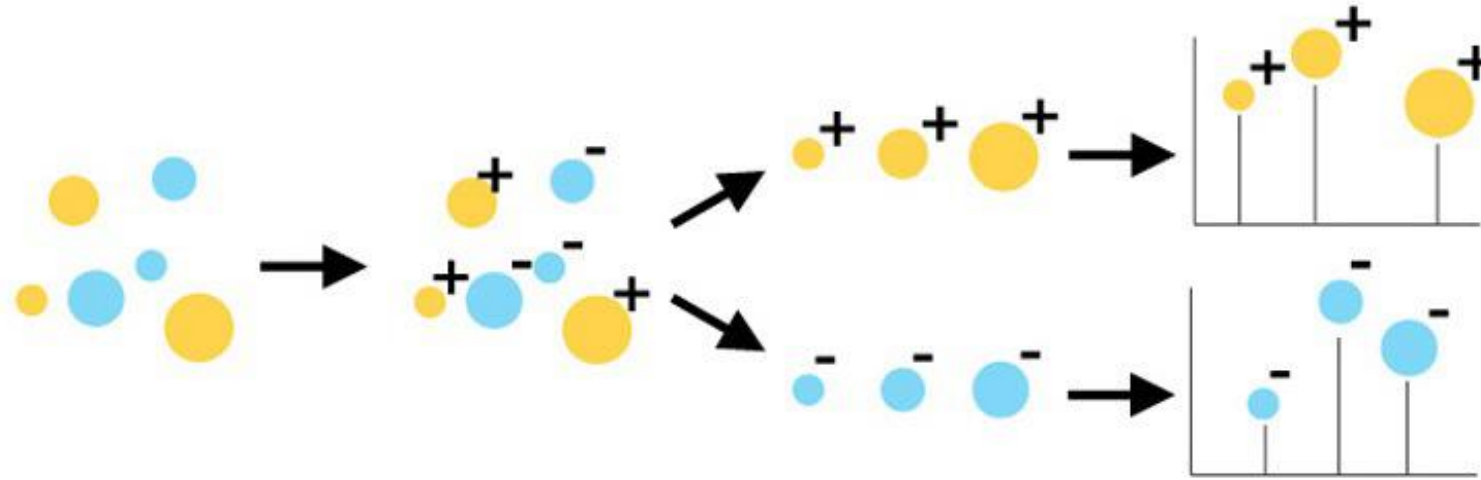
# Today's learning targets

- Main physics principles used for particle detection
- Bethe-Bloch formula describing ionisation losses
- Measurement of momentum and energy of the particles
- Combining different particle detection methods in modern particle physics experiments
- Examples of operating experiments

# Particle detection

- Typical particle size:  $\leq 10^{-15}$  m (proton radius)
- Wavelength reached by an electron microscope:  $\lambda \sim 10^{-10}$  m
- Visualizing the particles by eye is impossible: **need an indirect detection mechanism with devoted instruments**
- Many different types of particle detectors depending on the information we want to obtain:
  - e.g. measurement of particle trajectory: scintillators, bubble or cloud chambers, wire chambers, semi-conductors, etc.
- All of them rely on the detection of a **perturbation** induced in matter by a passing particle
- In most cases, the perturbation is either an **ionisation** (electrical signal) or **excitation** (scintillation light) of atoms
  - **electromagnetic** interaction between the passing particle and the atomic electrons (works only for charged particles and photons)
- All detectors have a sensitive volume in which the perturbations occur:
  - gas (e.g.  $Ar$ ,  $CO_2$ )
  - liquid (e.g. water,  $C_3H_8$ )
  - solid (e.g. Si, emulsion, ice)

# Ionisation



- A track of positive and negative ions is formed by a charged particle that kicks out an electron from the atom
- The energy loss per unit length traversed by the particle due to ionisation is given by the Bethe-Bloch formula:

$$\frac{dE}{dx} \approx -4\pi\hbar^2 c^2 \alpha^2 \frac{nZ}{m_e v^2} \left\{ \ln \left[ \frac{2\beta^2 \gamma^2 c^2 m_e}{I_e} \right] - \beta^2 \right\}$$

- $v = \beta c$  – the speed of the traversing particle
- $Z$  – atomic number of the material
- $n$  – the number density
- $I_e \sim 10Z$  eV – effective ionization potential of the material averaged over all atomic  $e^-$

# Ionisation in various materials

- The rate of ionisation energy loss does not depend significantly on the material except through its density  $\rho$ :

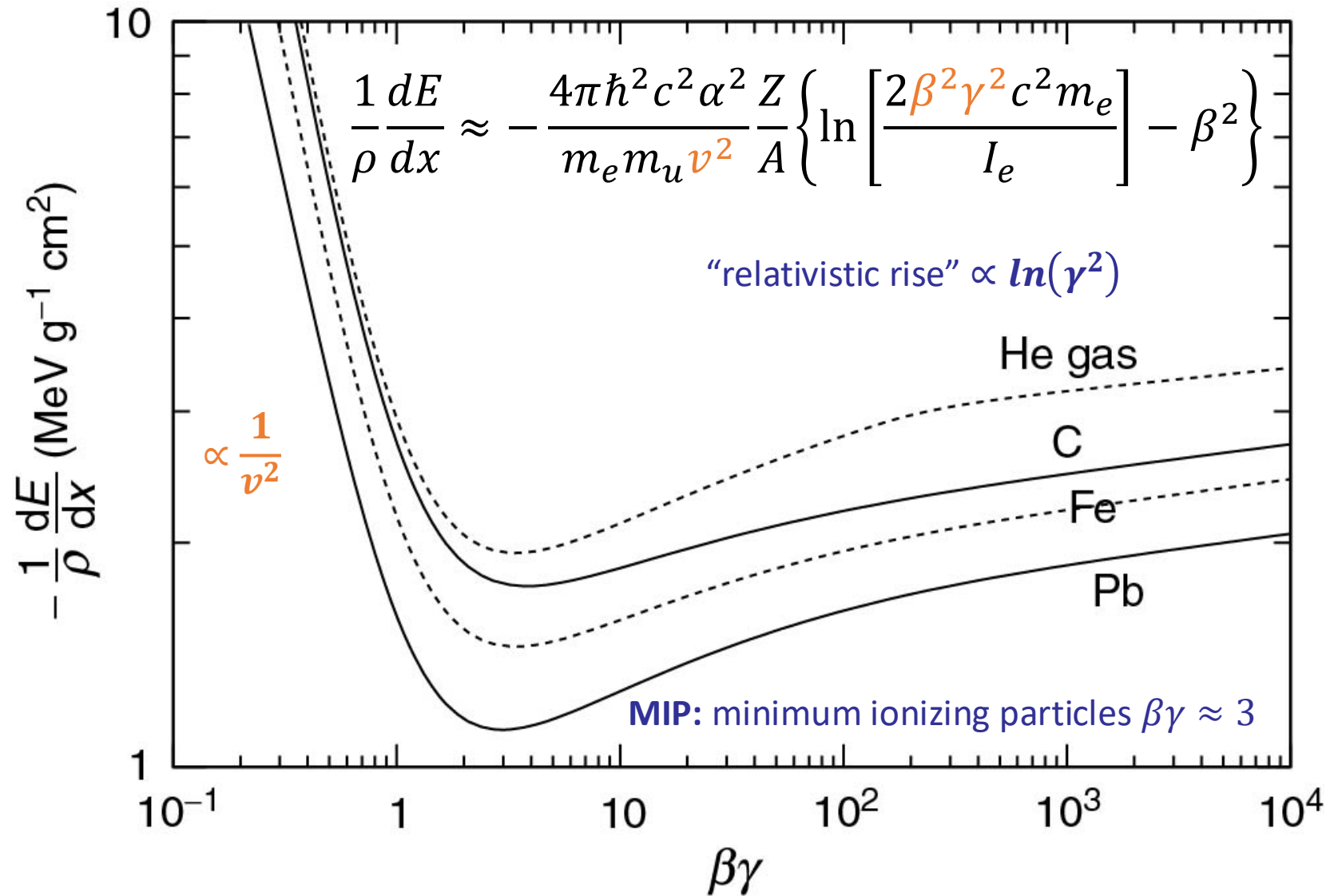
$$n = \frac{\rho}{Am_u}$$

- $A$  – atomic mass number
- $m_u = 1.6 \times 10^{-27}$  kg is the unified atomic mass unit

$$\frac{1}{\rho} \frac{dE}{dx} \approx - \frac{4\pi\hbar^2 c^2 \alpha^2 Z}{m_e m_u v^2 A} \left\{ \ln \left[ \frac{2\beta^2 \gamma^2 c^2 m_e}{I_e} \right] - \beta^2 \right\}$$

- $\Rightarrow \frac{1}{\rho} \frac{dE}{dX} \propto \frac{Z}{A} \approx \text{const}$

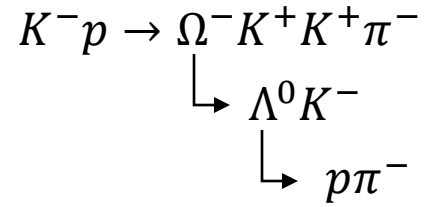
# Ionisation graph



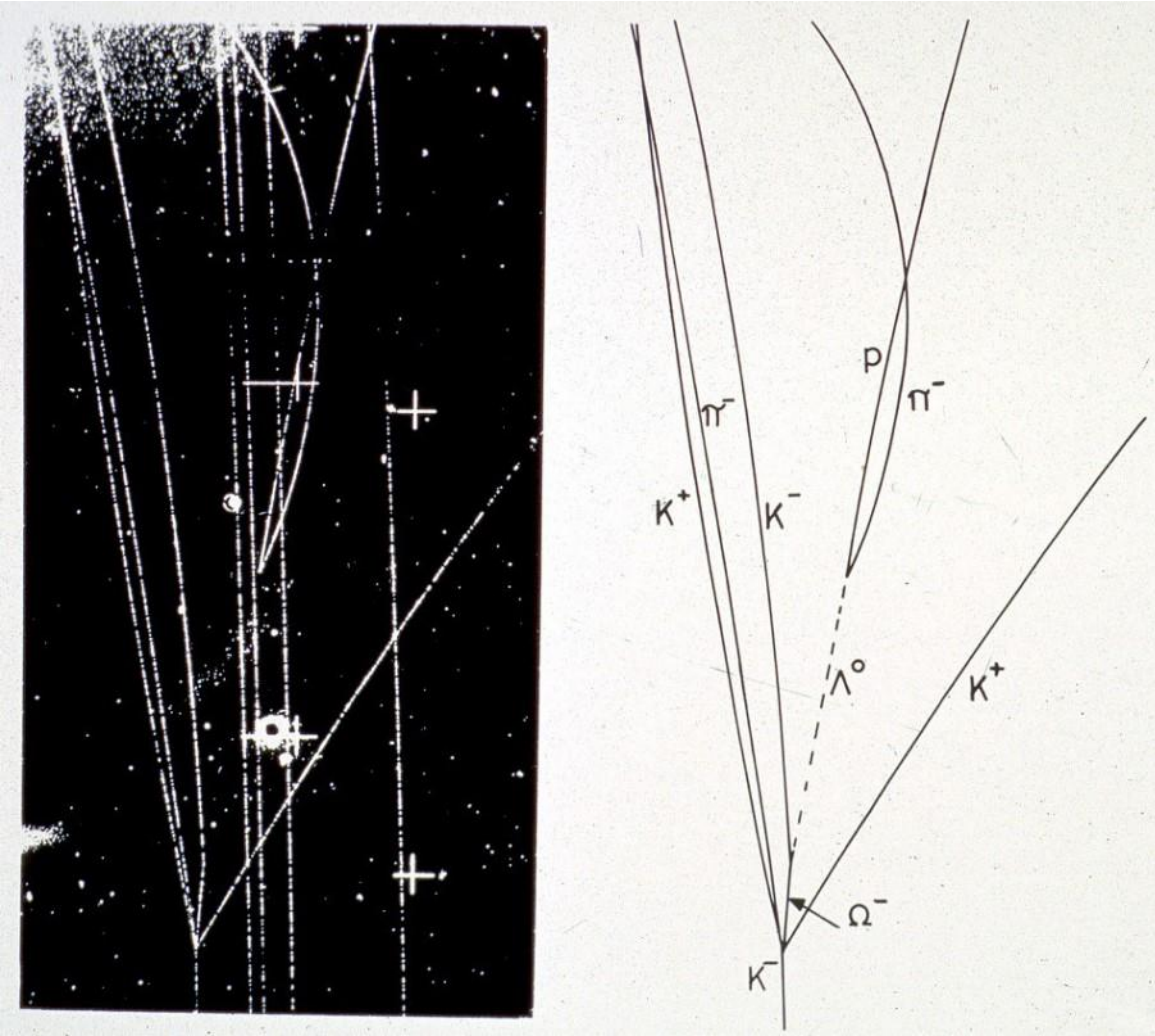
- In case no other energy losses present for a particle, at MIP level it can travel a long distance
  - e.g. muons in iron lose 13 MeV/cm and have a range of several meters.

# Tracking detectors

Bubble chamber:  
 $\Omega$  production and decay

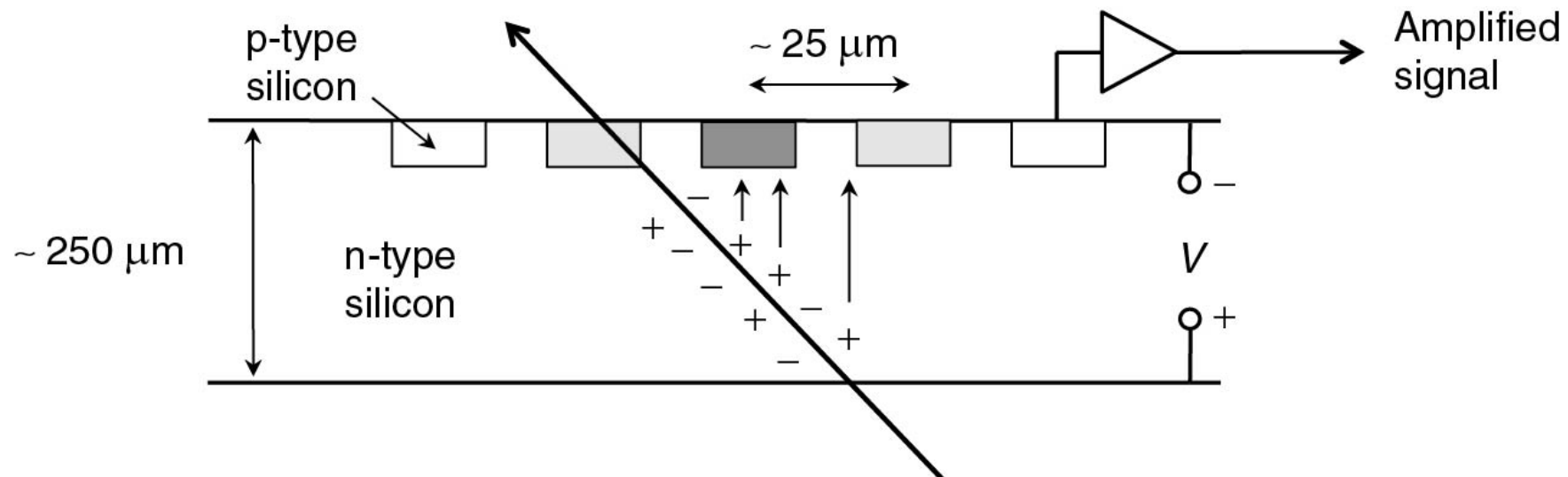


- There are many ways to collect information about the ionisation track
- Charged particles can be visualized
- Cloud chamber (supersaturated water or alcohol vapour; ions lead to condensation)
- Bubble chamber (see left; superheated transparent liquid, e.g. liquid nitrogen)
  - requires taking pictures and subsequent analysis  $\Rightarrow$  very slow
- Nuclear emulsion (photographic plate)
  - used in contemporary low-rate experiments, e.g. neutrino interaction detection



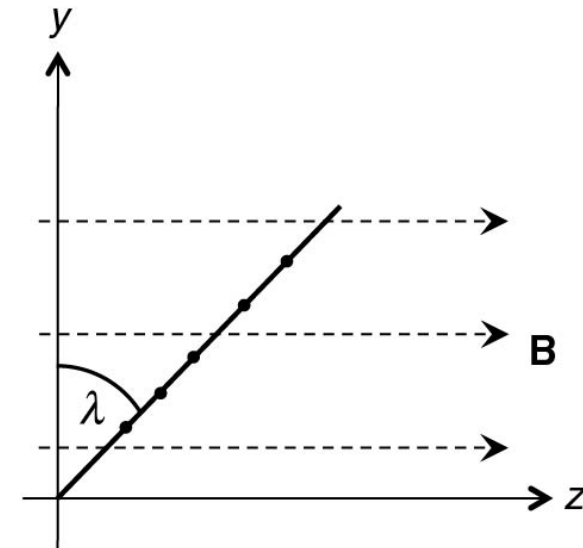
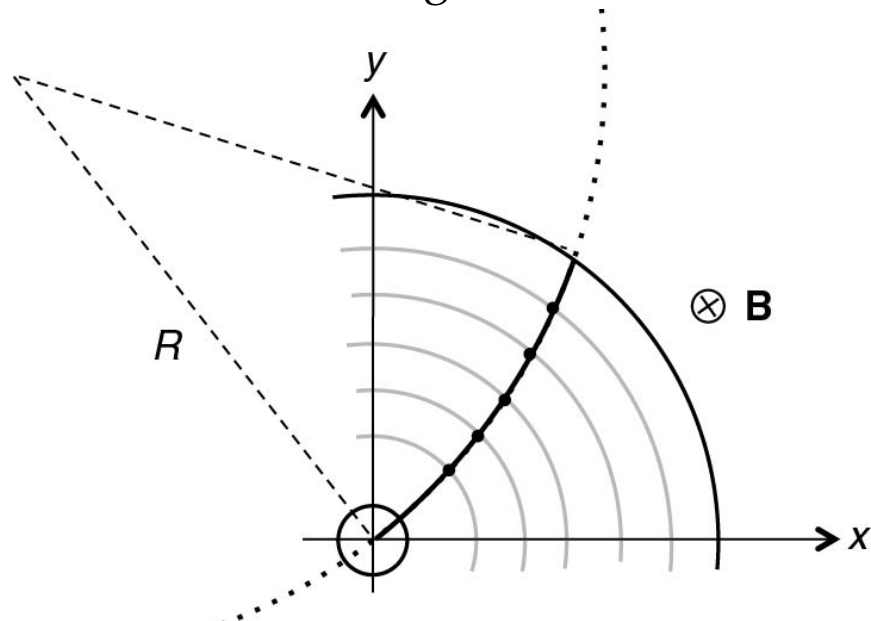
# Tracking detectors

- Most commonly-used technologies for track detection with electronic readout
- Wire chambers filled with gas
  - usually offer large spatial resolution  $\mathcal{O}(0.1 - 1 \text{ mm})$
  - used far from the interaction point, e.g. muon measurement and identification, tracking in fixed target experiments
- Silicon pixels or strips (semiconductors)
  - can provide resolution down to  $\mathcal{O}(10\mu\text{m})$
  - typically used near the interaction point to reconstruct many tracks and see displaced vertices



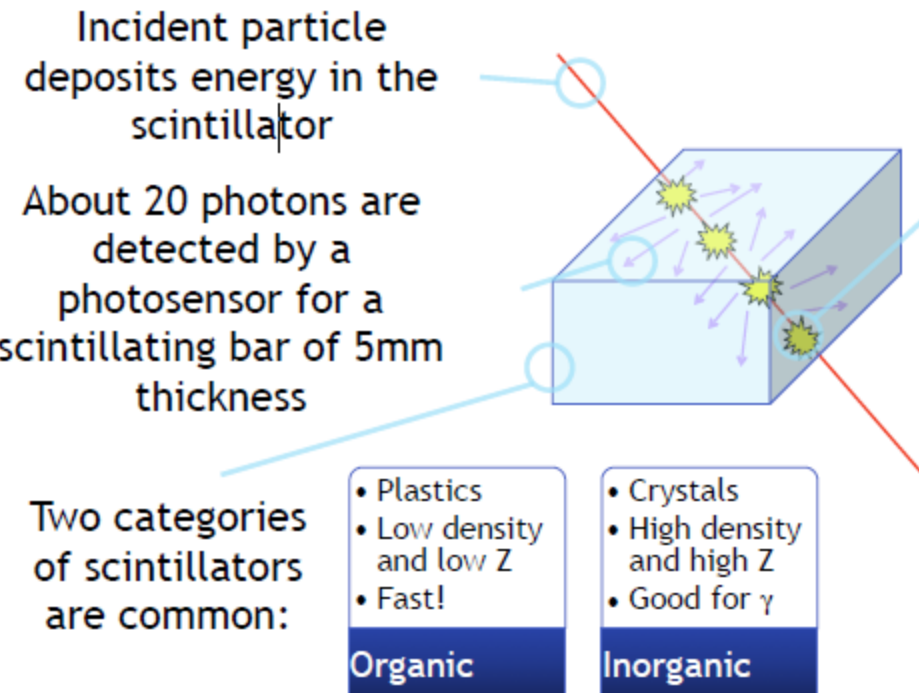
# Momentum measurement

- Complementing a tracking detector with magnetic field can measure  $p$  and  $q$
- $\frac{mv^2}{2} = q(\vec{v} \times \vec{B})$  for a perpendicular  $v$  component
- $p \cos\lambda = qBR$  (in SI) with pitch angle  $\lambda$
- $p \cos\lambda[\text{GeV}] = 0.3BR[\text{Tm}]$  (in HEP)
- We can obtain  $R$  and  $\cos\lambda$  from the reconstructed particle trajectory and knowledge of the  $B$
- Example: 100 GeV  $\pi^\pm$  in 4T magnetic field  $R = 100$  m  $\Rightarrow$  excellent spatial resolution is needed



# Scintillation

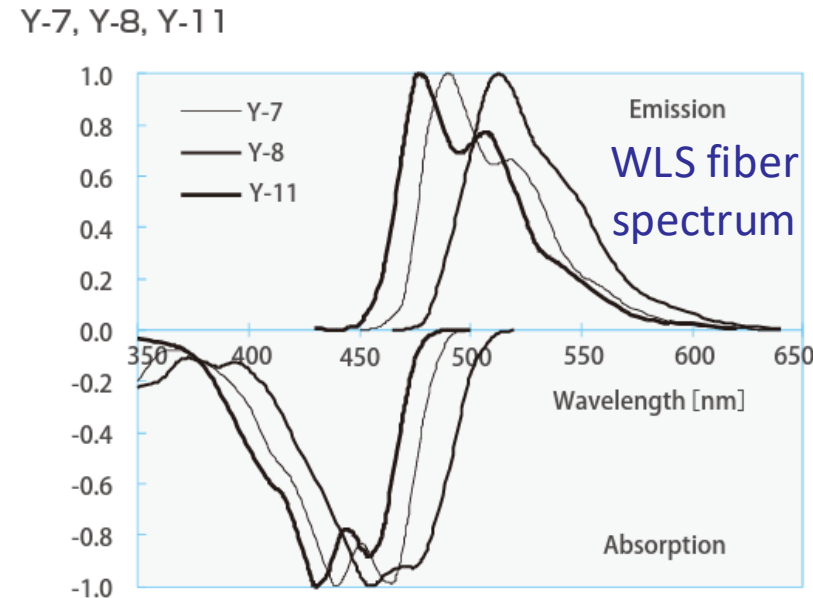
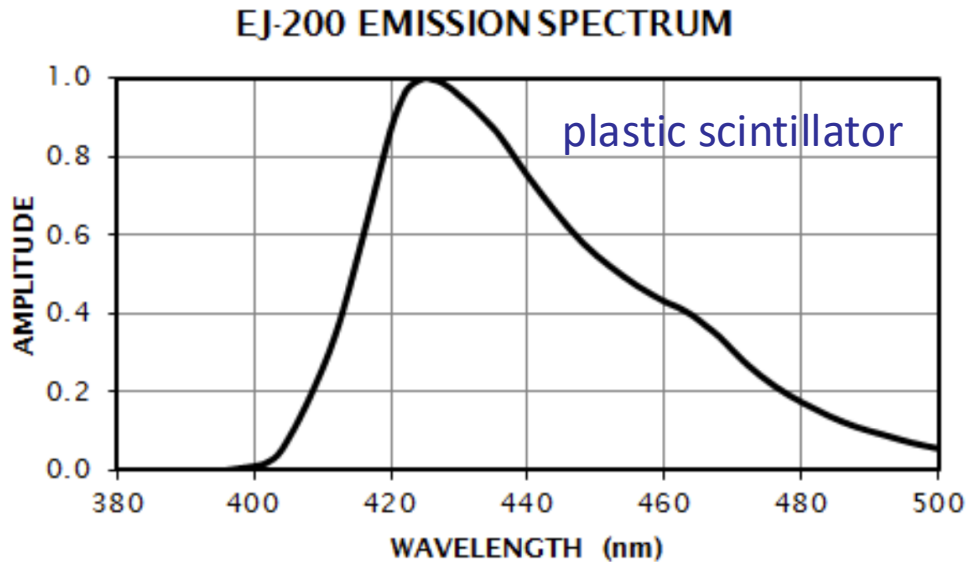
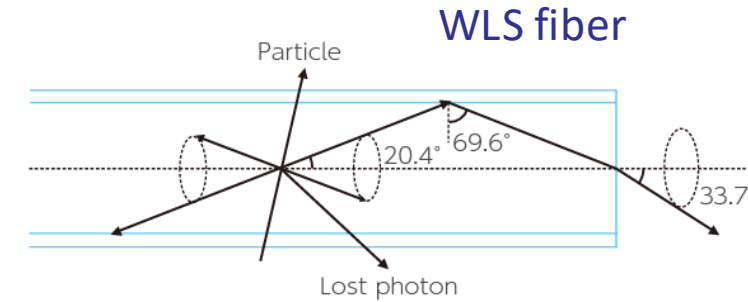
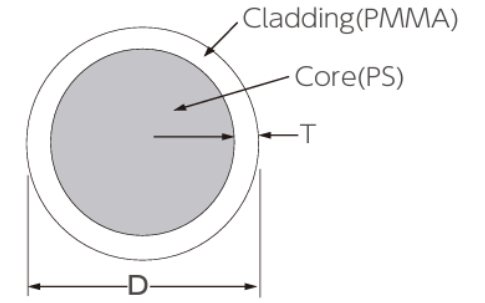
- Scintillator molecules are excited by a traversing charged particle or a photon which leads to emission of photons
- If the medium is transparent to the emitted photons, they can be detected
- Light isolation of the scintillator is important
- The light is guided to photodetectors which convert the photons to electrons, creating electric signal



- Scintillators are used in many applications
  - security and industry: radiation monitoring
  - physics: LHCb tracker (organic scintillator), CMS (inorganic scintillator), NA62 hadron calorimeter (organic scintillator)
  - medical: (TOF-) PET scanner

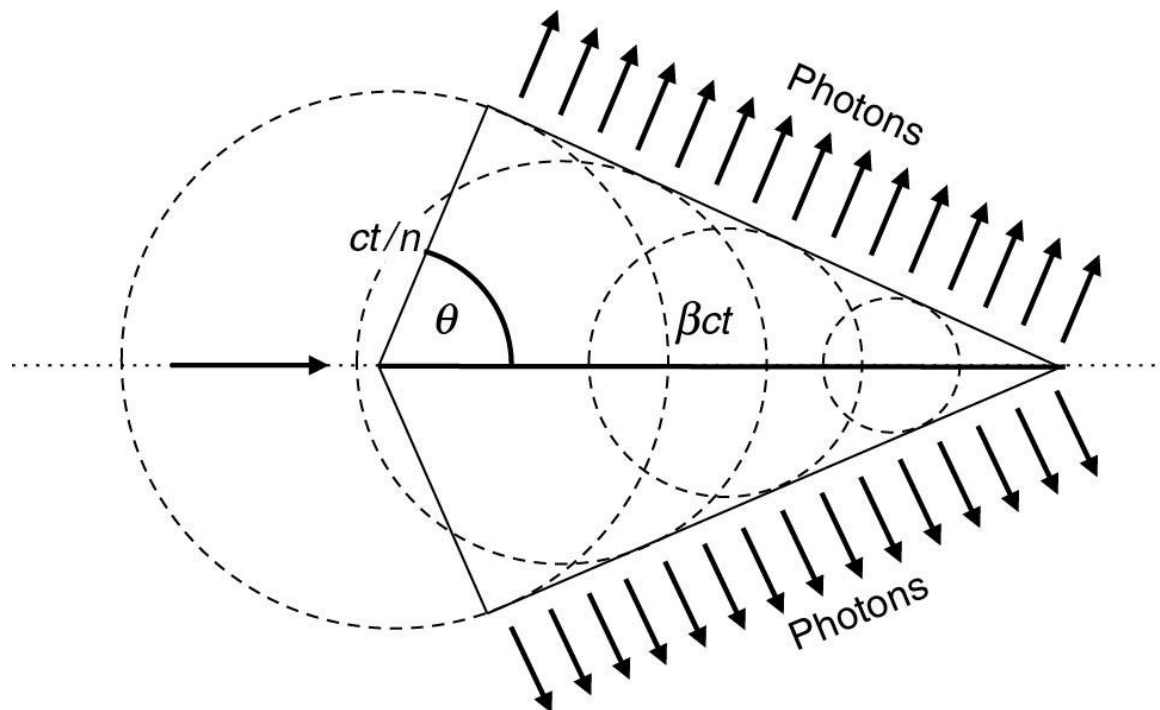
# Scintillation detector: example

- **Hadron calorimeter of NA62:** alternating iron plates and plastic scintillator strips with wavelength-shifting (WLS) fibers glued inside
- Charged particles deposit energy in the strips, leading to photon emission
- The photons are absorbed by the WLS fibers reemitted inside the fiber material and guided to photo-multiplier tubes (PMTs)
- WLS fibers reemit photons in the green part of the spectrum (higher detection efficiency)



# Cherenkov radiation

- Charged particles traversing a dielectric medium with refractive index  $n$  polarizes the molecules in the medium
- After the excitation the molecules return to an unpolarized state through the emission of photons
- If the velocity of the particle is greater than the speed of light in that medium  $v > c/n$ , constructive interference occurs and radiation is emitted as coherent wavefront at a fixed angle  $\theta$  along the trajectory of the particle
- The emitted light can be collected by photo-multiplier tubes (PMTs), capable of detecting single photons



- Light produced at an angle  $\theta$

- $\cos\theta = \frac{1}{\beta n}$

- light emission if  $\beta > 1/n$

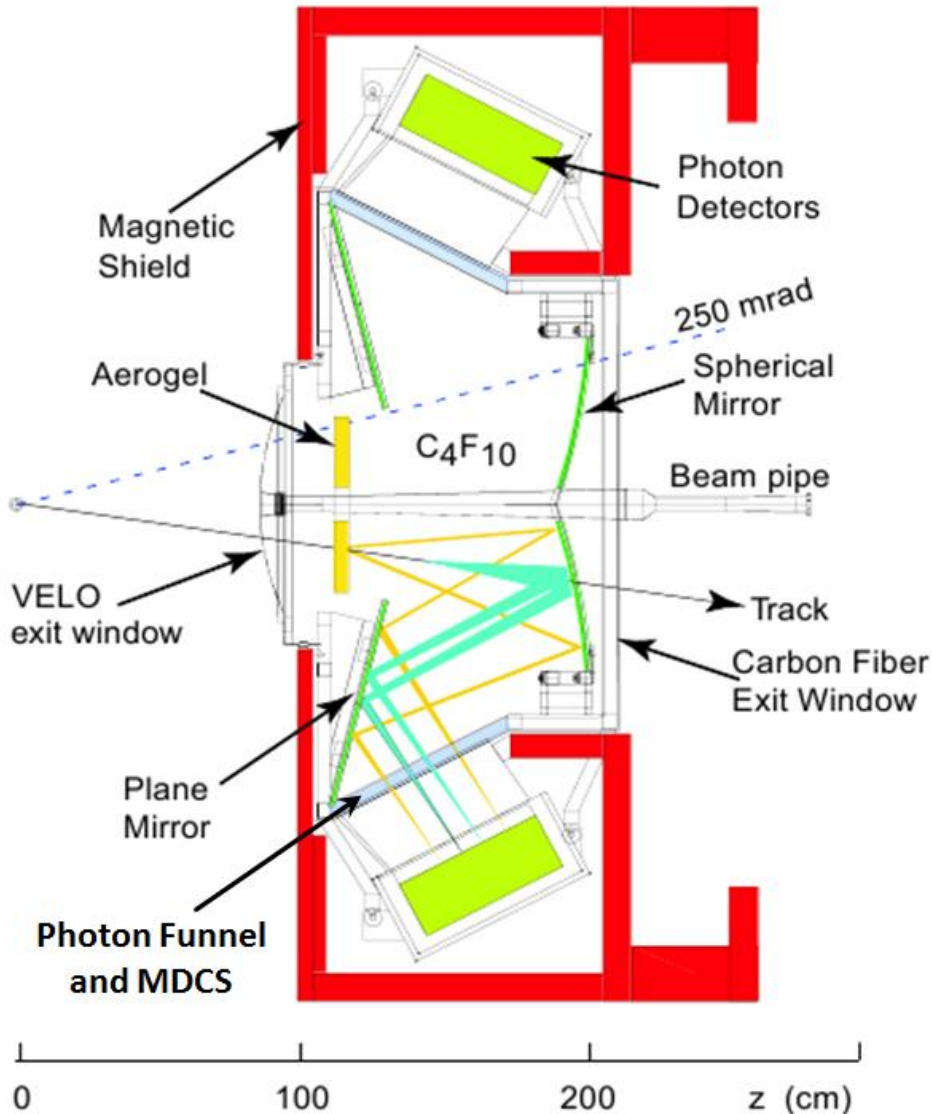
- $\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$

- $\Rightarrow m < p\sqrt{n^2 - 1}$

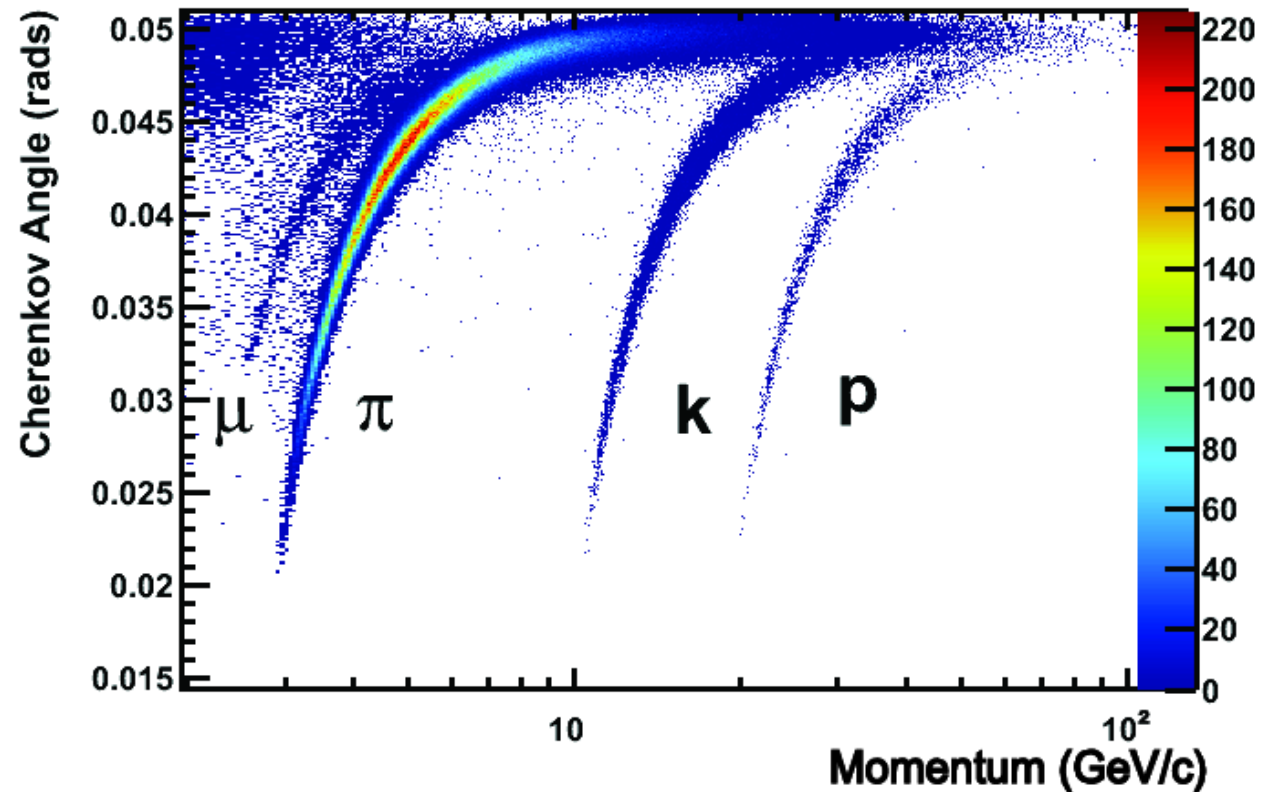
- For a given  $p$  helps identifying the passing particles

# RICH: Ring Imaging Cherenkov system at LHCb

- At LHCb, the RICH system is used to identify different hadrons:  $\pi^\pm, K^\pm, p$



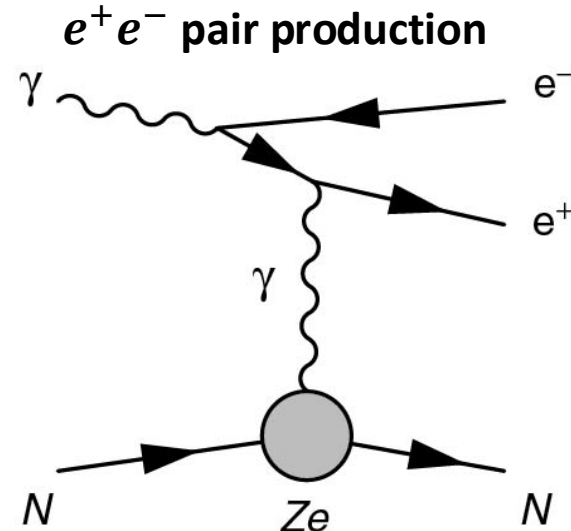
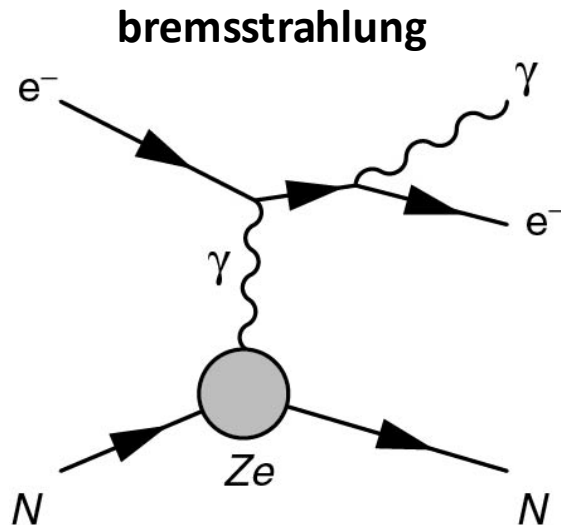
- Reconstructed Cherenkov angle as a function of track momentum in the  $C_4F_{10}$  radiator of the RICH detector



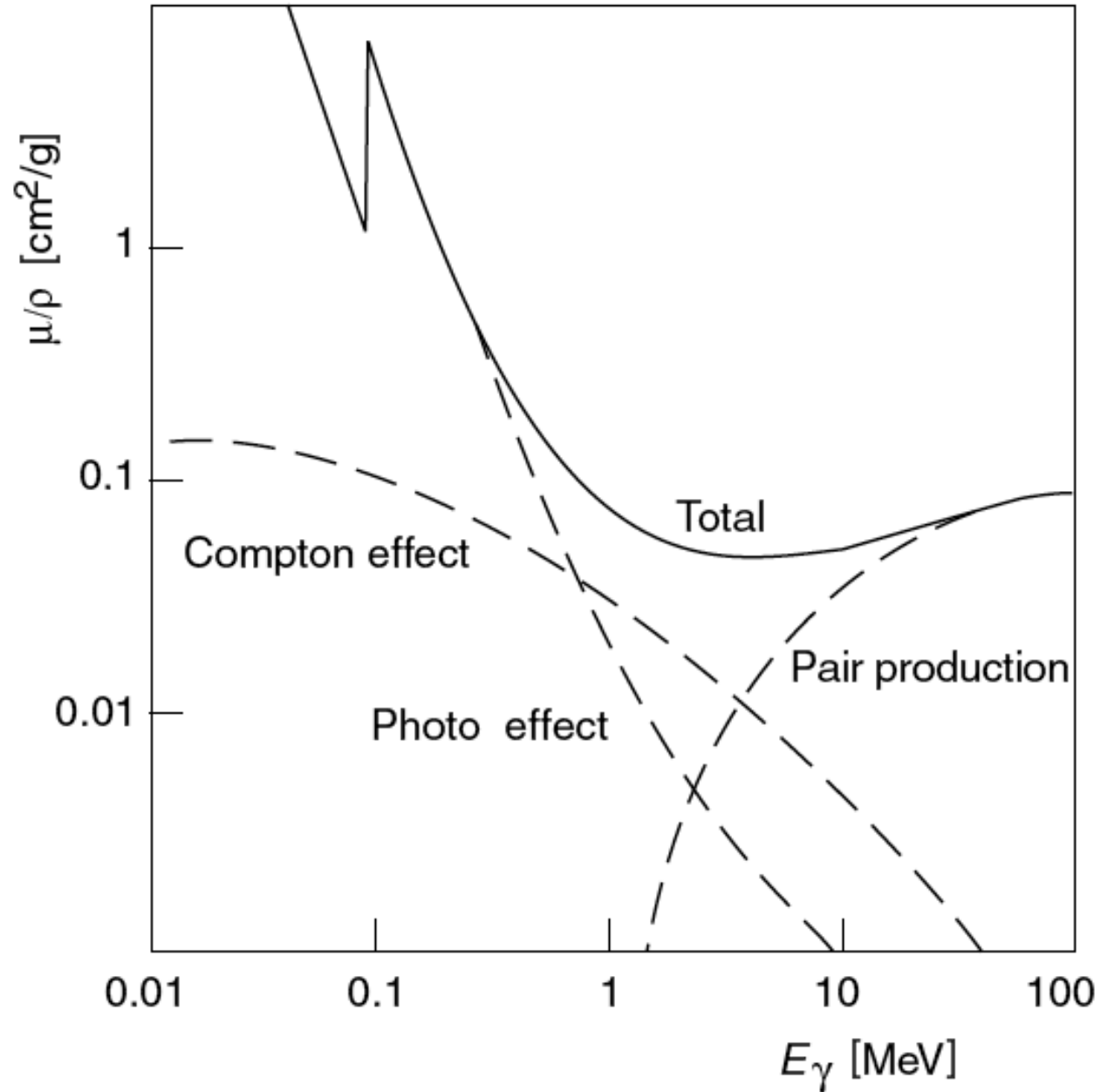
- Measure momentum  $p$  in the tracker, speed  $v$  in the RICH and derive the particle mass and therefore its type

# Bremsstrahlung and $e^+e^-$ production

- Bremsstrahlung (braking radiation) is the main energy loss mechanism for  $e^\pm$  at energies above the critical energy  $E_c \sim 800/Z$  MeV – a condition “always” fulfilled in current particle physics experiments
- Bremsstrahlung  $\propto 1/m_{particle}^2 \Rightarrow$  not so important for  $\mu^\pm$ , heavier particles for which ionisation losses dominate
- Three main interactions between photons and matter:
  - Photoelectric effect: the photon is absorbed by an atomic electron that is ejected from the atom (valid for  $E_\gamma < 1$  MeV)
  - Compton scattering:  $\gamma e^- \rightarrow \gamma e^-$  important at  $E_\gamma \sim 1$  MeV
  - $e^+e^-$  pair production: dominant energy loss mechanism for photons with  $E_\gamma > 1.02$  MeV



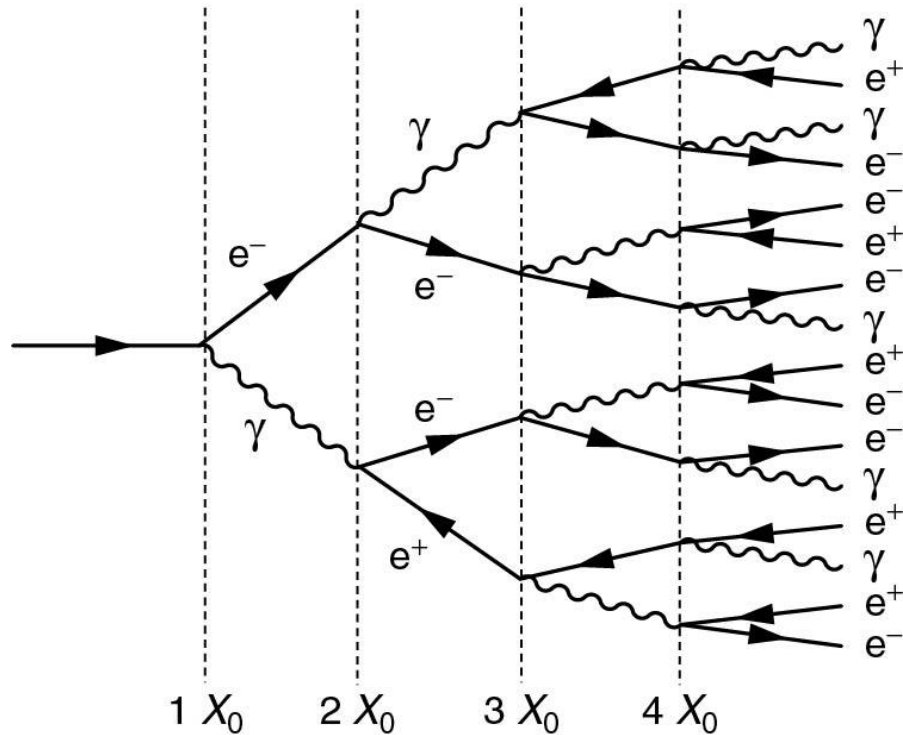
# Interactions of photons with matter



# Radiation length

- Important characteristics of materials: **radiation length  $X_0$**
- Average distance over which the energy of an electron is reduced by bremsstrahlung by a factor  **$e(\sim 2.7)$**
- $\approx 7/9$  of the mean free path of the  $e^+e^-$  pair-production for a photon

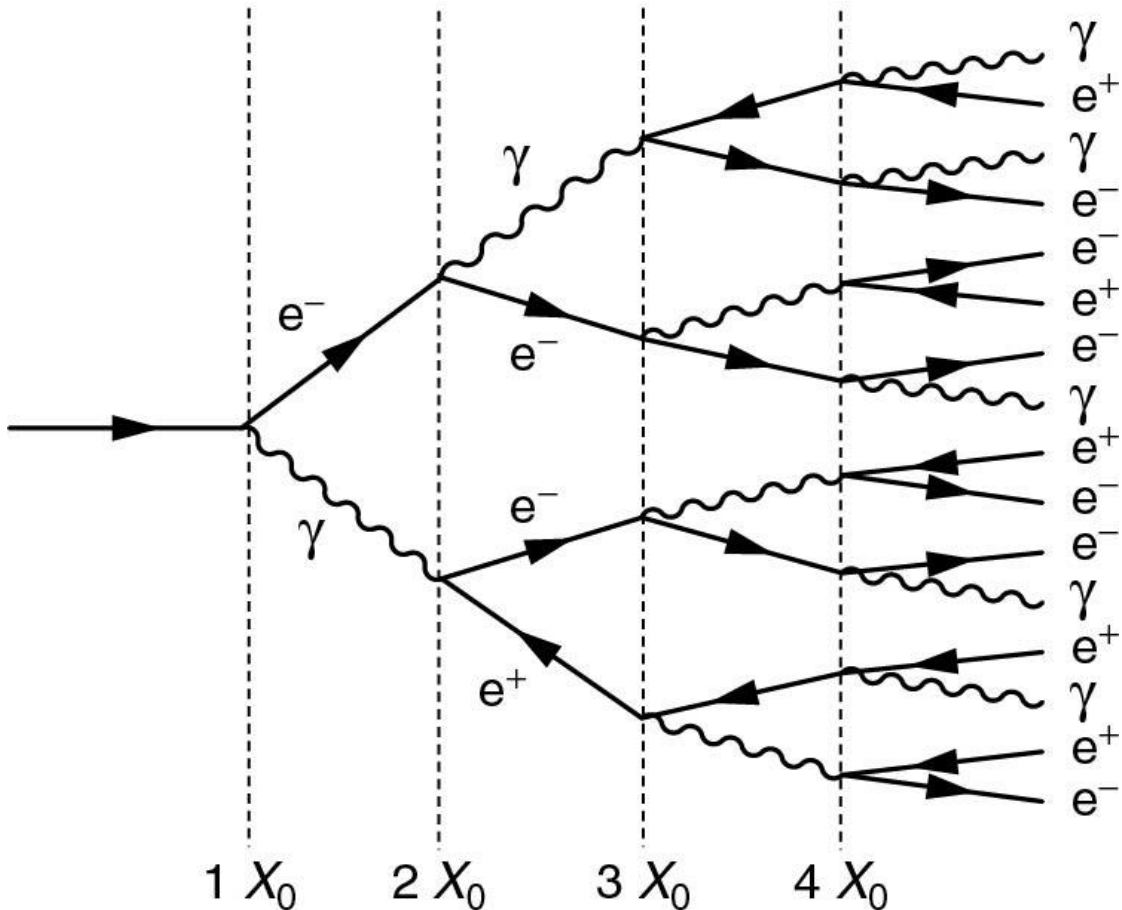
$$X_0 \approx \frac{1}{4\alpha n Z^2 r_e^2 \ln\left(\frac{287}{\sqrt{Z}}\right)}, \quad r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.8 \times 10^{-15} \text{ m}$$



- Examples of typical high-Z materials :
  - $X_0(\text{Fe}) = 1.76 \text{ cm}$
  - $X_0(\text{Pb}) = 0.56 \text{ cm}$
  - $\Rightarrow X_0$  is rather short

# Electromagnetic showers

- **Electromagnetic (EM) shower:** alternating bremsstrahlung and  $e^+e^-$  pair production process
- Number of particles  $\sim$  doubles every  $X_0 \Rightarrow$  after  $nX_0$  the average energy of particles is  $\langle E \rangle \sim \frac{E}{2^n}$
- Shower development stops when  $\langle E \rangle < E_c$  (shower maximum)



$$x_{\max} = \ln(E/E_c) / \ln 2$$

## Example:

- Shower development in lead:
  - $E_c \sim 10$  MeV
  - $X_0(\text{Pb}) = 0.56$  cm
- A 100 GeV EM shower has a maximum at  $x_{\max} \sim 13 X_0$
- $\Rightarrow x_{\max} = 7.28$  cm (compact shower)

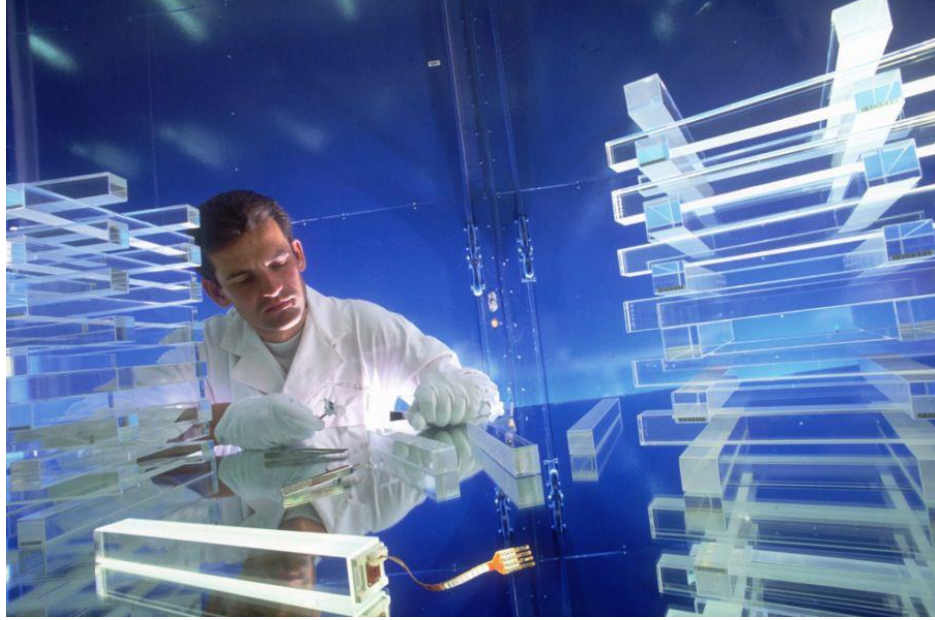
# Electromagnetic calorimeters

- Electromagnetic calorimeters is used to measure energy of photons and electrons by fully absorbing them through shower development
- Main parameters are energy and position resolution:
  - $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$
  - $\sigma_{x,y} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$  (linear term  $\propto 1/E$  usually less relevant for position resolution)
  - a: photoelectron statistics (sometimes called *stochastic* term), including effects due to the sampling fraction (how frequently we “sample” the shower profile)
  - b: electronics noise
  - c: calibration uncertainty and crystal non-uniformity

# Types of electromagnetic calorimeters

- **Homogeneous calorimeters:** constructed from a material combining the properties of an absorber and a detector
  - scintillation (scintillating crystals, liquid noble gas)
  - ionisation (liquid noble gas)
  - Cherenkov light (lead glass or heavy transparent crystals)
- **Sampling calorimeters:** simpler, more economical way to measure  $\gamma/e^\pm$  energy if energy resolution is not crucial
  - composed of alternating layers of absorber and sensitive material (e.g. plastic scintillator)
- Best energy resolution at low energies is achieved by *crystal calorimeters*
  - example: CMS ECAL  $\Rightarrow a = 2.7\%$ ,  $b = 155 \text{ MeV}$ ,  $c = 0.55\%$
- *Sampling calorimeters* have typical values of  $a \sim 6 - 25\%$ 
  - example: LHCb ECAL  $\Rightarrow a = 10\%$ ,  $c = 1\%$

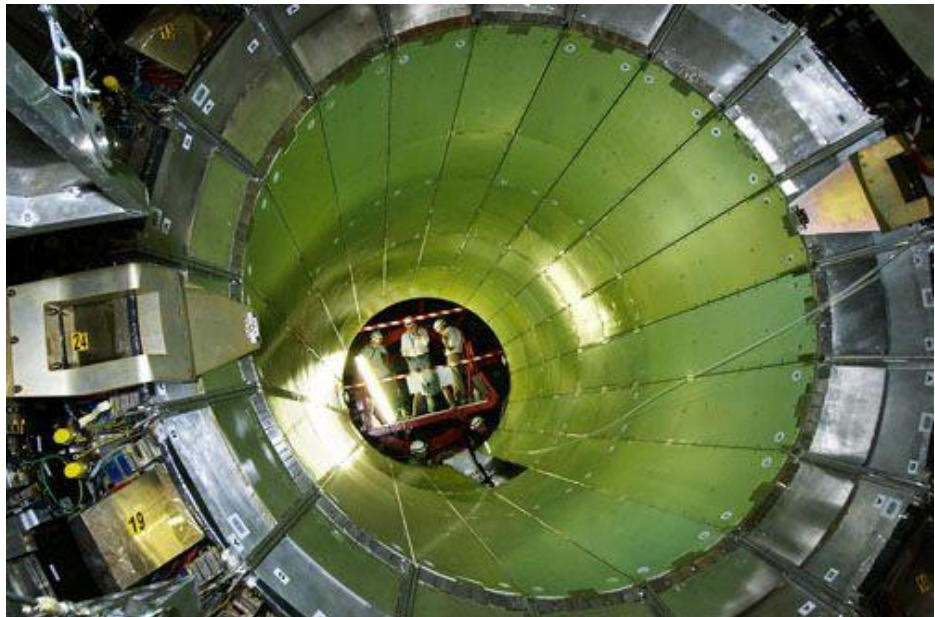
# Electromagnetic calorimeter of CMS



- Inorganic scintillation crystals (lead tungstate  $\text{PbWO}_4$ )
  - each crystal weighs 1.5 kg with a volume of a coffee cup
  - ECAL contains  $\sim 80\,000$  such crystals, each of which took two days to grow in the lab
  - it took 10 years to produce mostly in Russia, partially in China

- ETH contribution

- crystal R&D and procurement
- development and tests of electronics components
- integration of the readout electronics
- detector control system
- signal pulse reconstruction

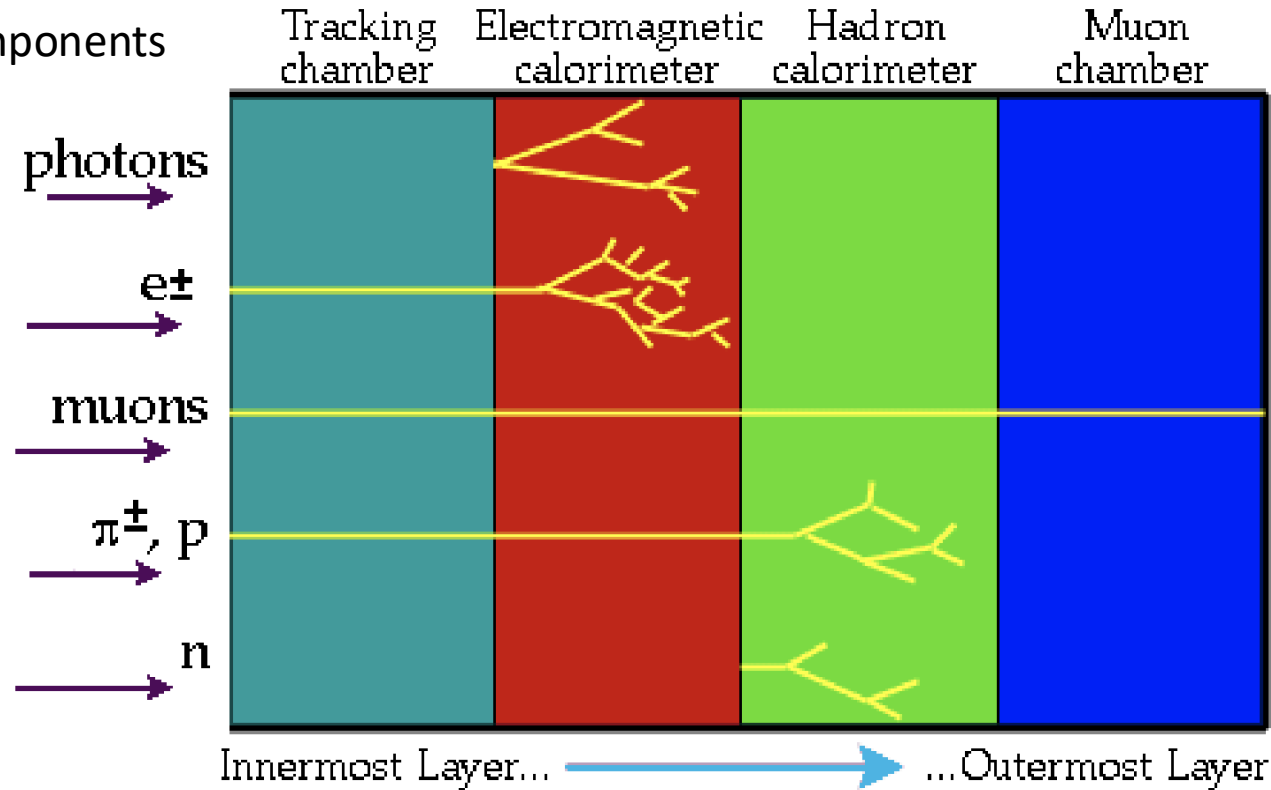


# Hadron calorimeters

- HCAL works along the same lines as ECAL
- Main difference is in the longitudinal shower development, determined by the average nuclear interaction length
$$\lambda_I \approx 35 \text{ g/cm}^2 A^{1/3} \gg X_0$$
  - scintillation (scintillating crystals, liquid noble gas)
  - ionisation (liquid noble gas)
  - Cherenkov light (lead glass or heavy transparent crystals)
- Typical reaction:  $p + \text{nucleus} \rightarrow \pi^+ + \pi^- + \pi^0 + \dots + \text{nucleus}^*$
- Shower from a 100 GeV hadron extends  $\sim 2 \text{ m}$  longitudinally and  $\sim 0.5 \text{ m}$  laterally
- Typically a sampling technology is used
- Fluctuations in the EM fraction of the shower (from  $\pi^0$ s) and the amount of energy lost in nuclear break-up lead to a typical  $\sigma_E/E \sim 50\%/\sqrt{E/\text{GeV}}$  (order of magnitude worse than for EM showers)

# Summary of particle detection

Sketched layout and main components of particle physics experiment



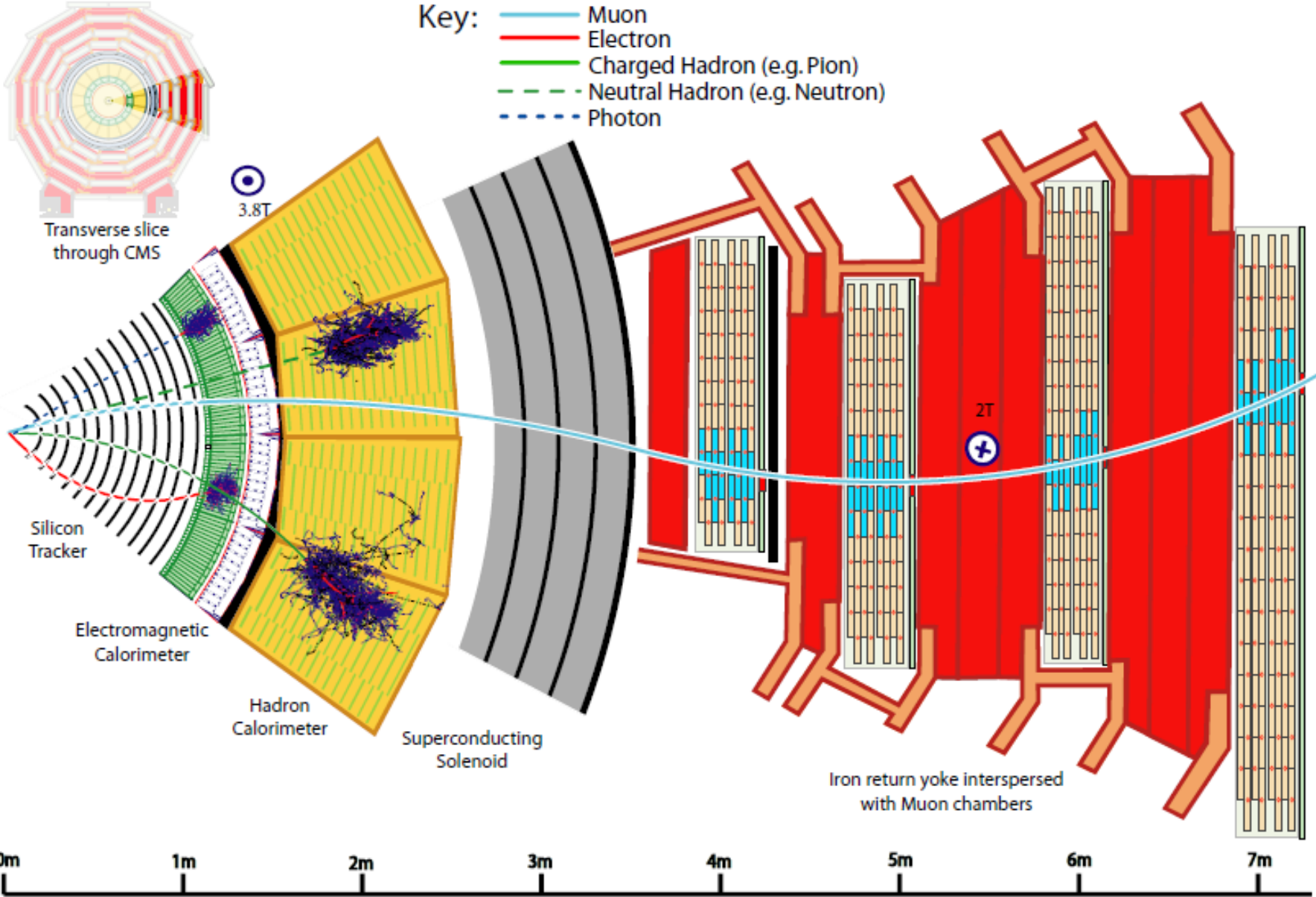
- Tracking detectors measure the momentum of charged particles and their charge
- Calorimeters measure the energy of the particles
- Cherenkov detectors allow to determine the speed/mass of the particle
- Relative position of various type of detectors is optimised to collect and correlate all possible information

# More information about particle detectors

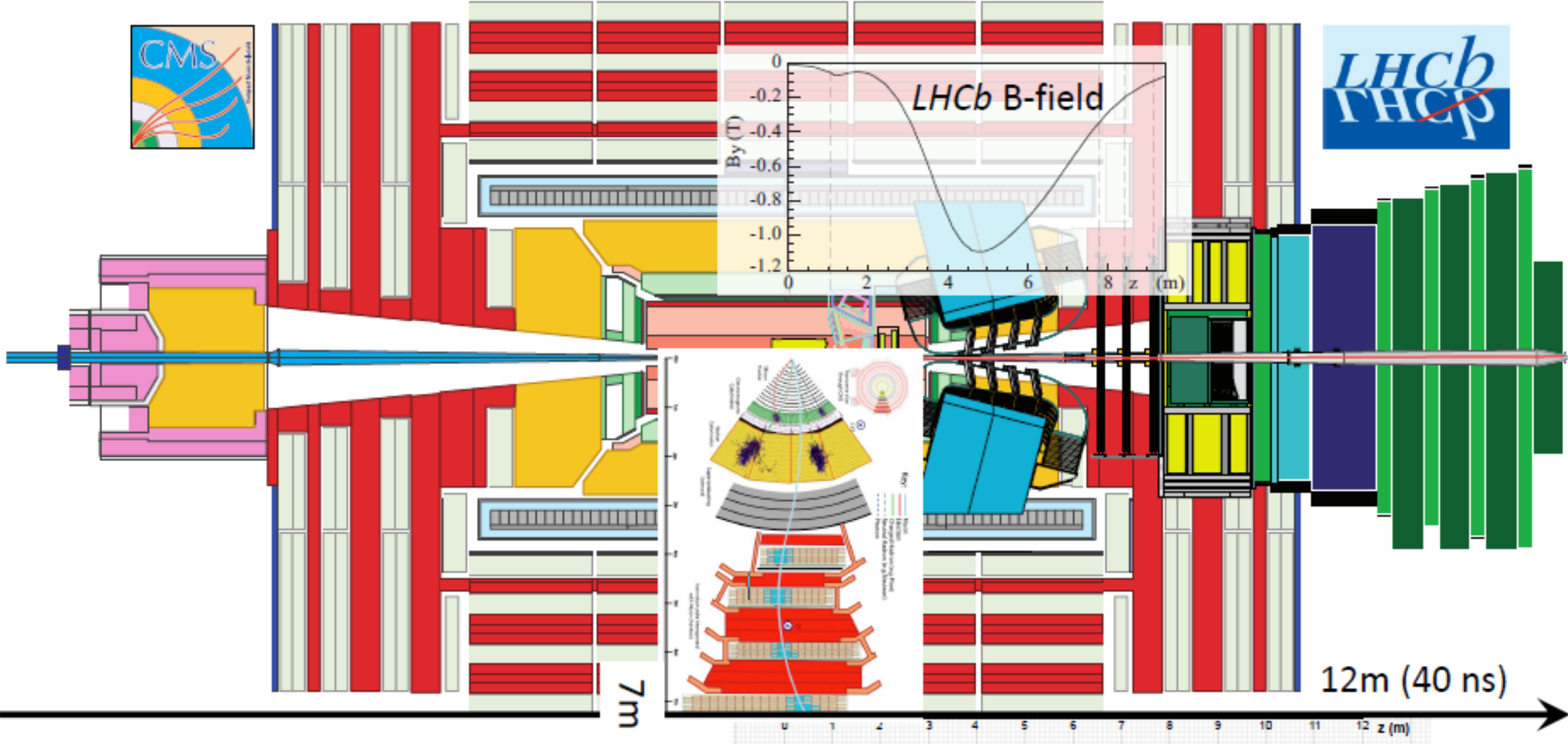
- A detailed detector review in a book by Claus Gruppen and Irene Buvat:
  - “Handbook of Particle Detection and Imaging” (2012)
  - Available from the publisher for free download
  - <https://link.springer.com/referencework/10.1007/978-3-642-13271-1>
- A dedicated one-semester course given in the fall semester (now) by Guido Haefeli:
  - PHYS-440 – Particle Detection
  - <https://edu.epfl.ch/coursebook/en/particle-detection-PHYS-440>
  - everybody with interest in experimental particle physics is strongly encouraged to follow it!

**Let's have a look at a few modern particle physics experiments at CERN!**

# Particles passing through detector: CMS

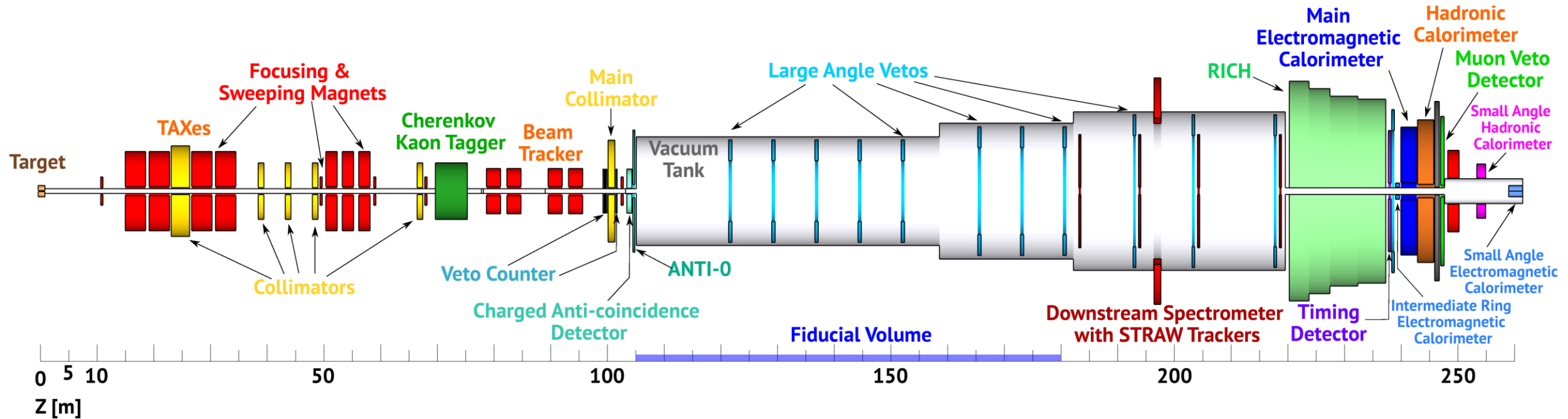


# Detectors visualized



- ATLAS and CMS have  $4\pi$  geometry and record almost the full information from the collision
- LHCb is instrumented in the forward direction and provides complementary coverage

# Detectors visualized

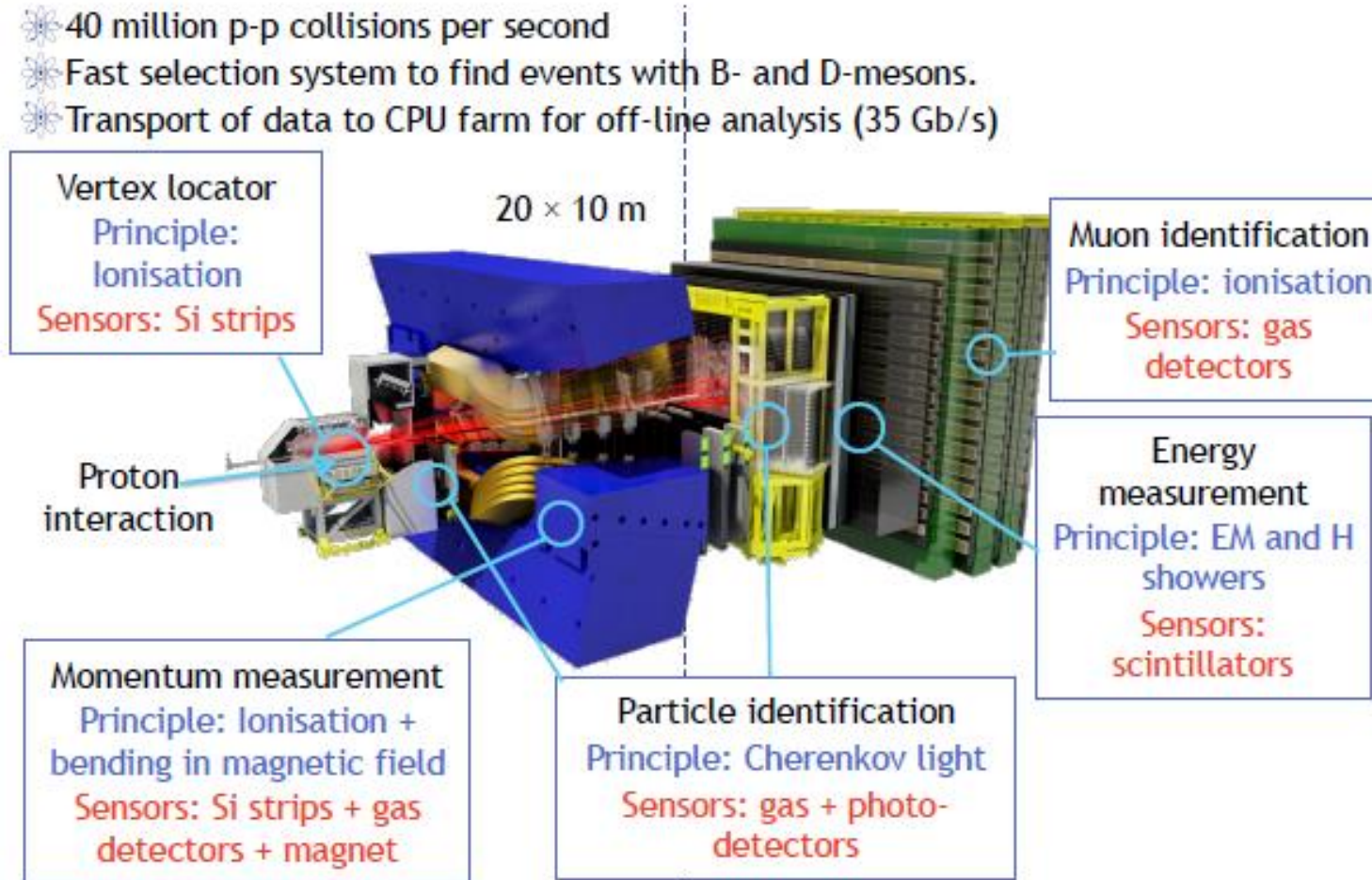


- Beam of 400 GeV protons hits the primary target
- Secondary unseparated beam of 75 GeV is created (mainly  $p, \pi^+, K^+$ ) and guided to the fiducial decay volume
- Significantly boosted  $K$  meson ( $\gamma \sim 150$ ) decays in flight in the fiducial decay volume  $\sim 100 - 170$  m from the target
- $4\pi$  coverage corresponds to  $\sim 50 \times 10^{-3}$  rad because of the high boost of the  $K$  meson particle

# LHCb subdetectors

- LHCb searches for the charge-parity (CP) violation in the decays of  $B$  and  $D$  mesons (containing  $b$  and  $c$  quarks) produced in  $pp$  collisions at the LHC
- Sizable CP violation can explain the observed asymmetry between matter and antimatter in the Universe

LHCb detector in  
Run 1 and 2  
(2011-2018)



# Summary of Lecture 3

## Main learning outcomes

- What are the main physics principles used in particle detection
- How to employ different detection methods to measure the characteristics of charged and neutral particles
- Examples of modern particle physics experiments which combine detection methods to study fundamental physics phenomena