Particle Physics I

Lecture 3: Particle detection

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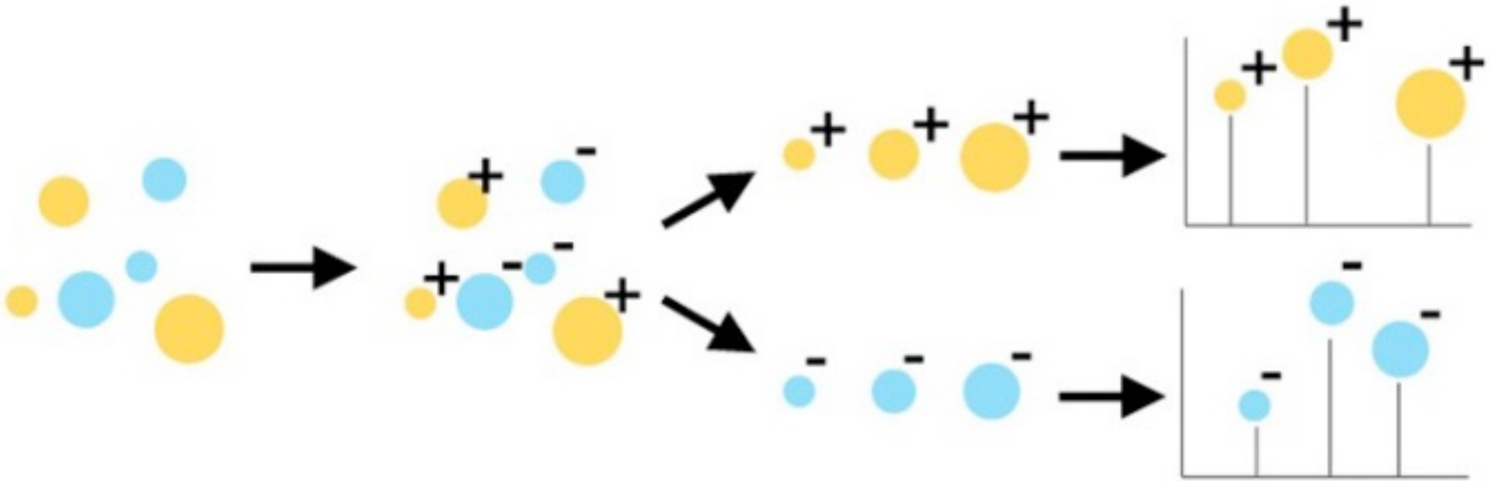
Today’s learning targets

- 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
- $I_e \sim 10\mathrm{Z\ eV}$ – 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 ρ:

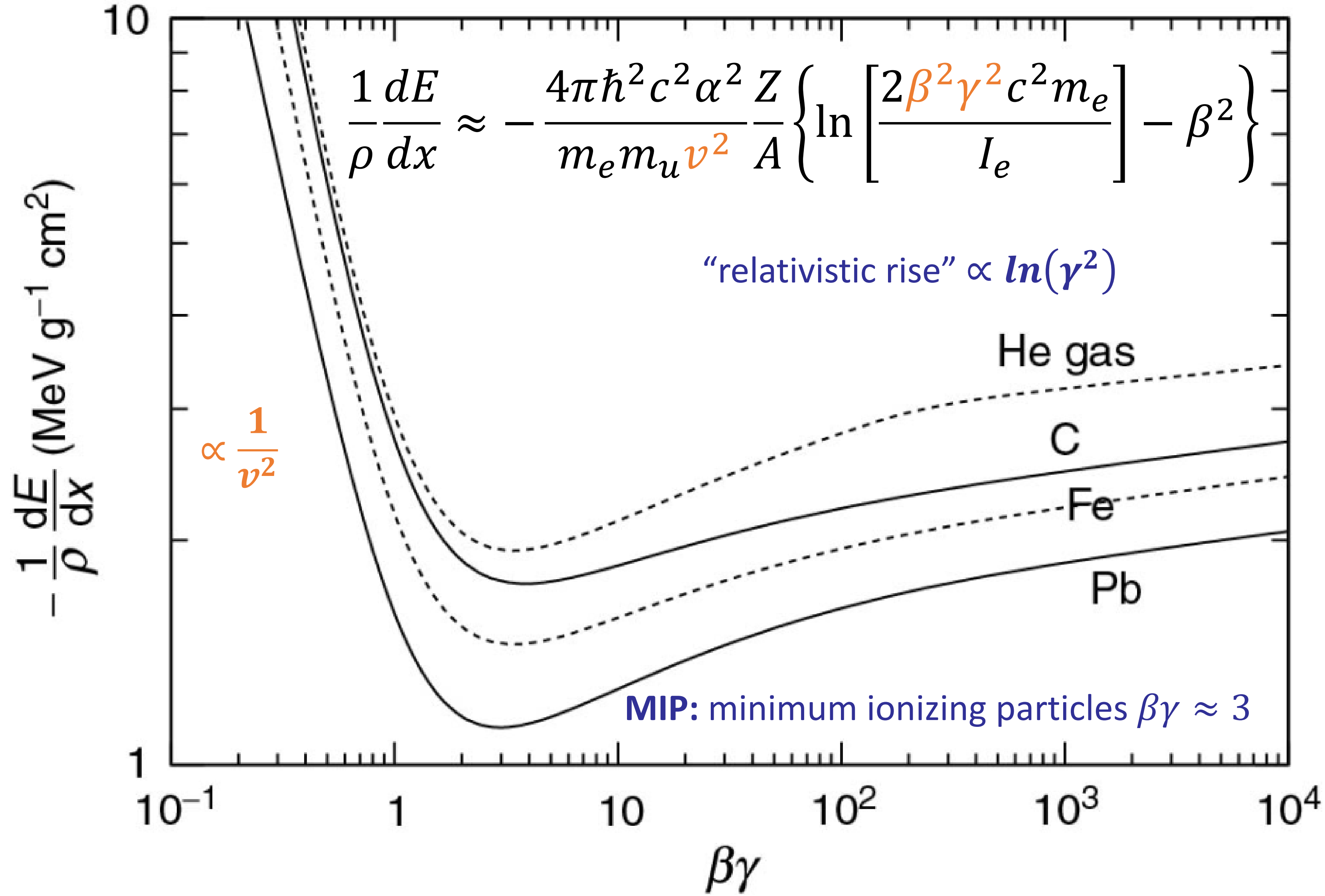
$$n = \frac{\rho}{A m_u}$$

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

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

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

Ionisation graph

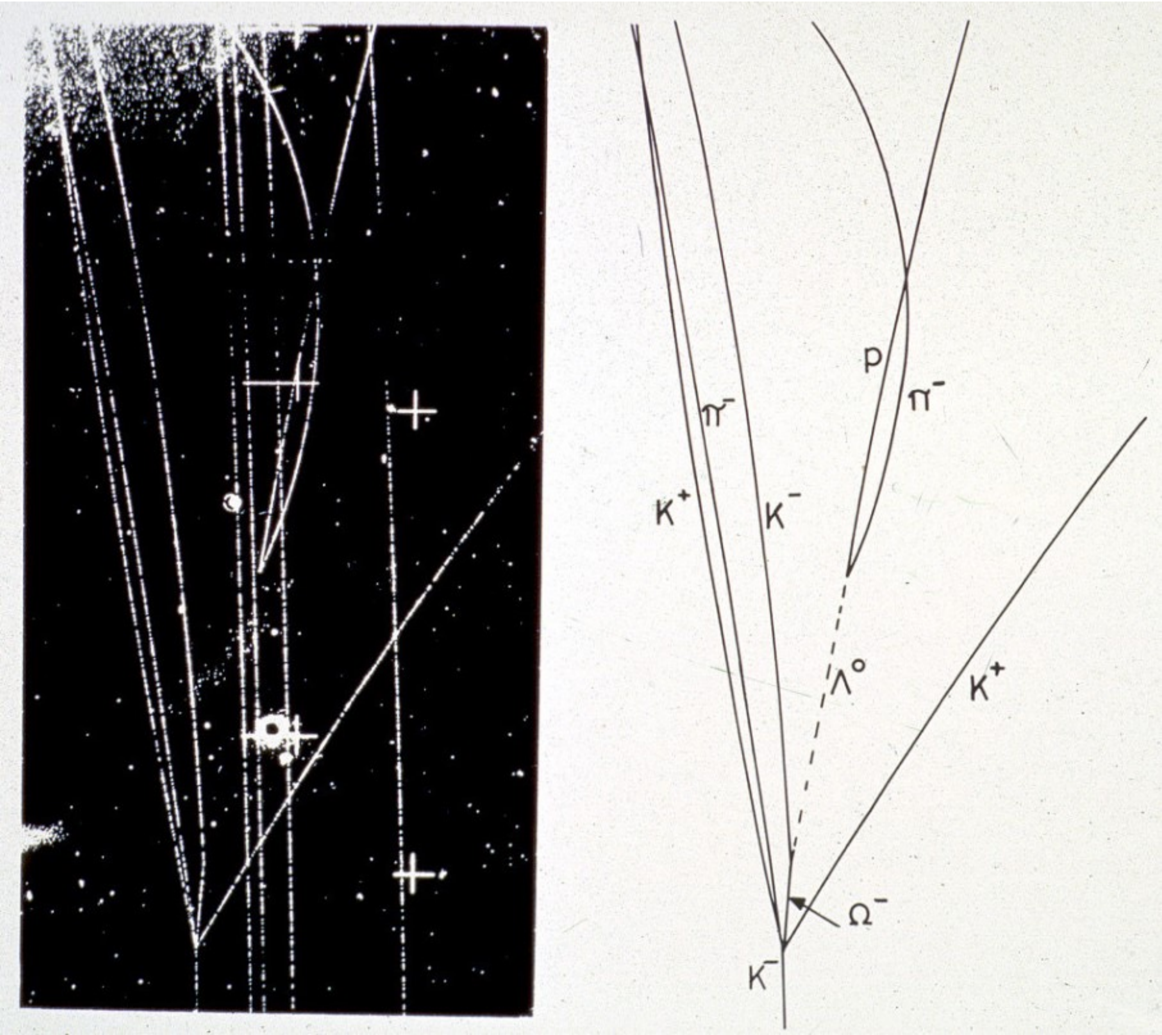


- In case no other energy losses present for a particle, at MIP level it can travel a long distance
    - e.g. muons in iron lose 13 MeV/cm and have a range of several meters.

Tracking detectors

Bubble chamber:
Ω production and decay

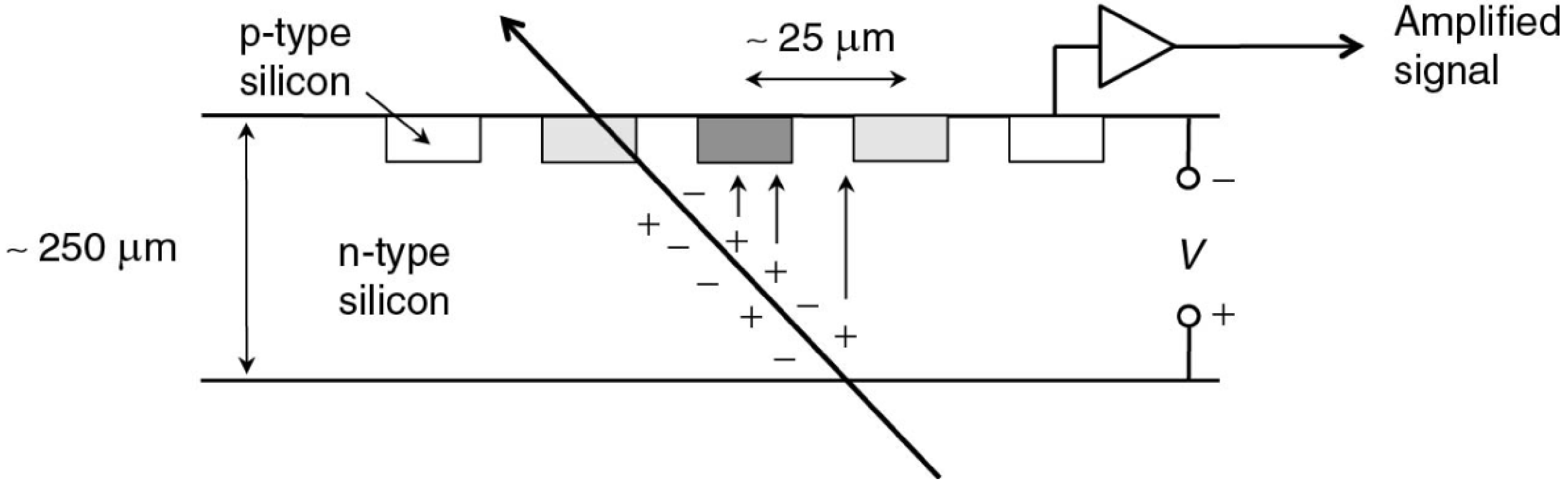
$$K^-p \to \Omega^- K^+ K^+ \pi^-$$
$$\hookrightarrow \Lambda^0 K^-$$
$$\hookrightarrow p\pi^-$$



- 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 $\Longrightarrow$ very slow
- Nuclear emulsion (photographic plate)
  - used in contemporary low-rate experiments, e.g neutrino interaction detection

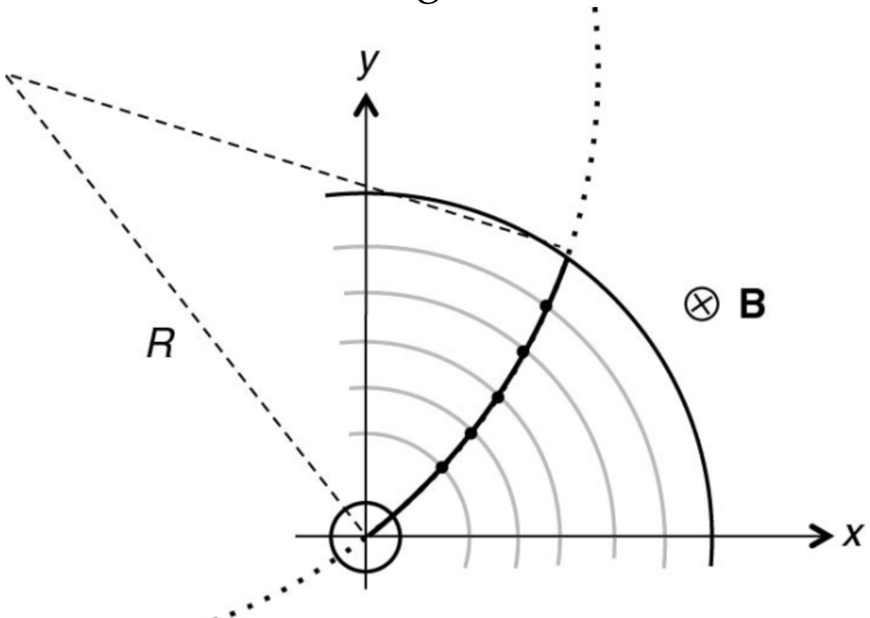
Tracking detectors

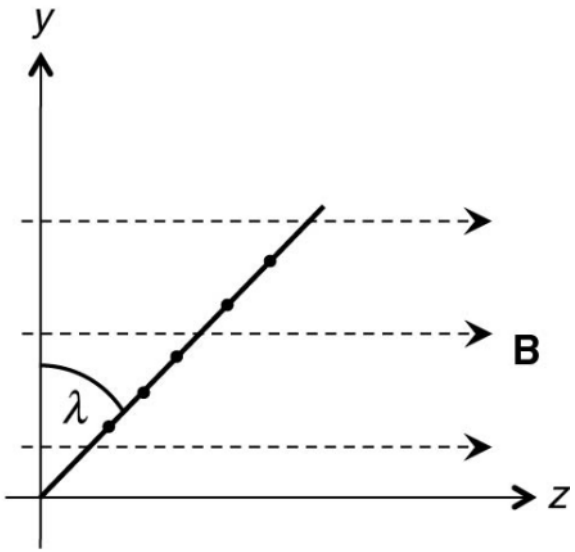
- Most commonly-used technologies for track detection with electronic readout
- Wire chambers filled with gas
  - usually offer large spatial resolution $\mathcal{O}(0.1 - 1\text{ mm})$
  - used far from the interaction point, e.g. muon measurement and identification, tracking in fixed target experiments
- 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

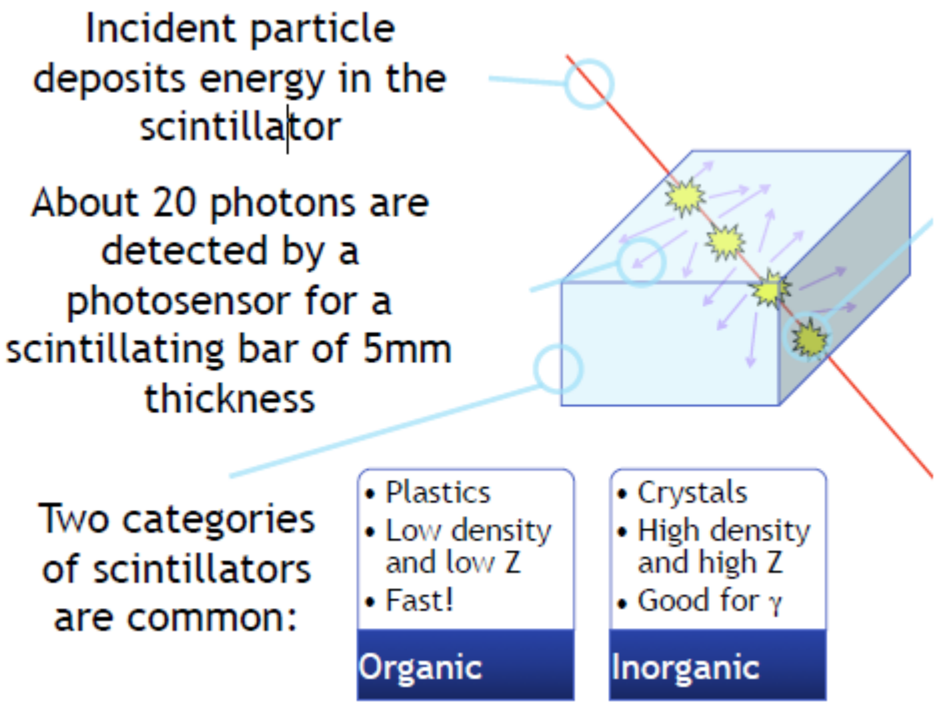
- Complementing a tracking detector with magnetic field can measure p and q
- $\frac{mv^2}{2} = q(\vec{v}\times\vec{B})$ for a perpendicular v component
- $p \cos\lambda = qBR$ (in SI) with pitch angle λ
- $p \cos\lambda[\text{GeV}] = 0.3BR[T\text{m}]$ (in HEP)
- We can obtain R and $\cos\lambda$ from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





Scintillation

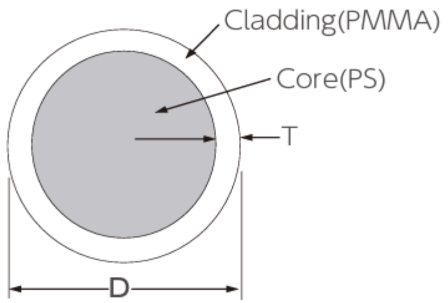
- Scintillator molecules are excited by a traversing charged particle or a photon which leads to emission of photons
- If the medium is transparent to the emitted photons, they can be detected
- Light isolation of the scintillator is important
- The light is guided to photodetectors which convert the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



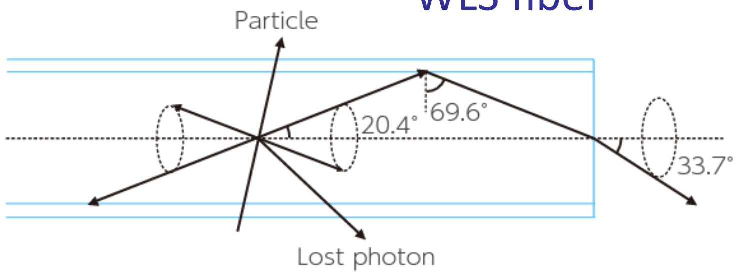
- Scintillator are used in many applications
  - security and industry: radiation monitoring
  - physics: LHCb tracker (organic scintillator), CMS (inorganic scintillator), NA62 hadron calorimeter (organic scintillator)
  - medical: (TOF-) PET scanner

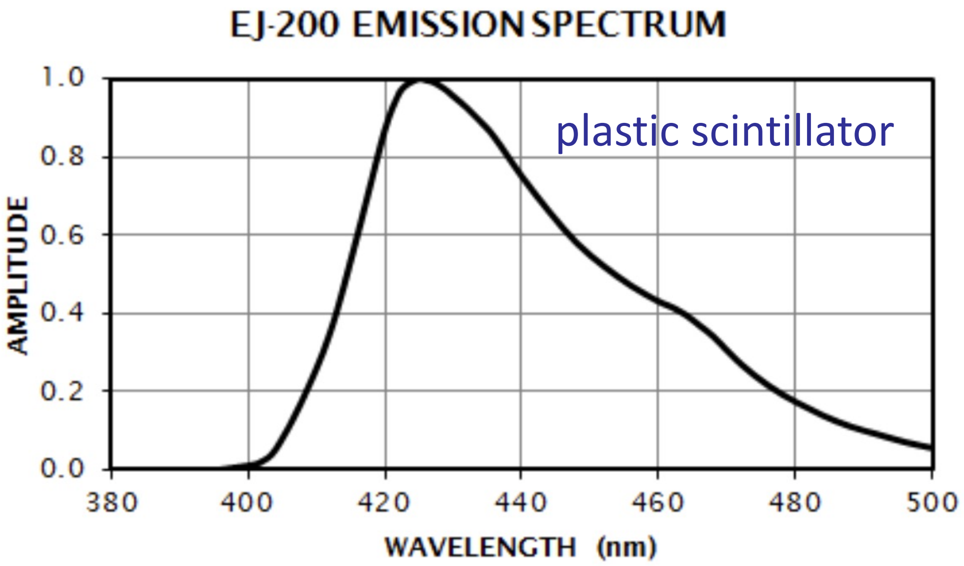
Scintillation detector: example

- 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)

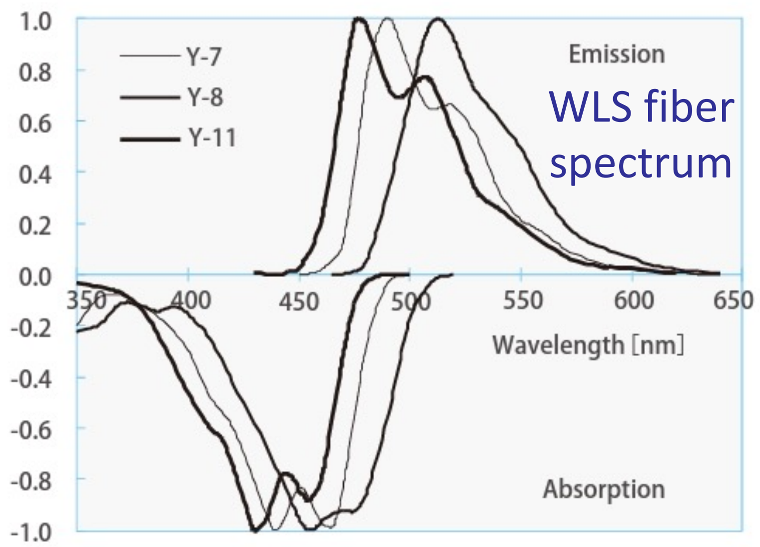


WLS fiber



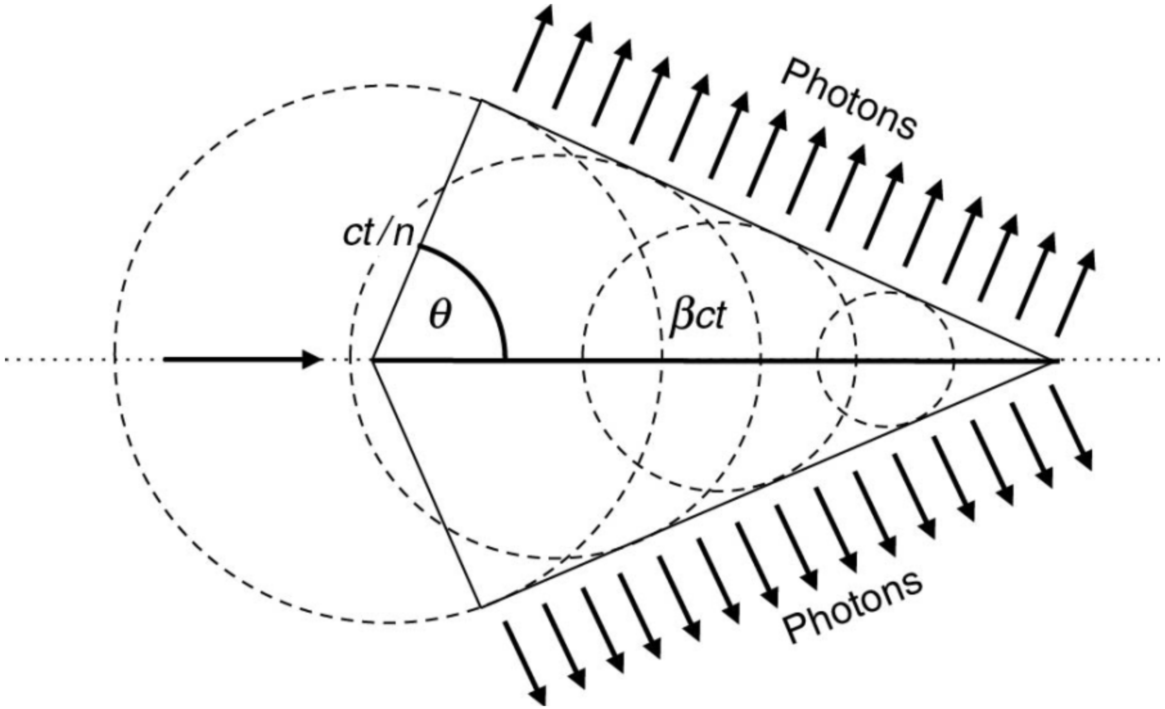


Y-7, Y-8, Y-11



Cherenkov radiation

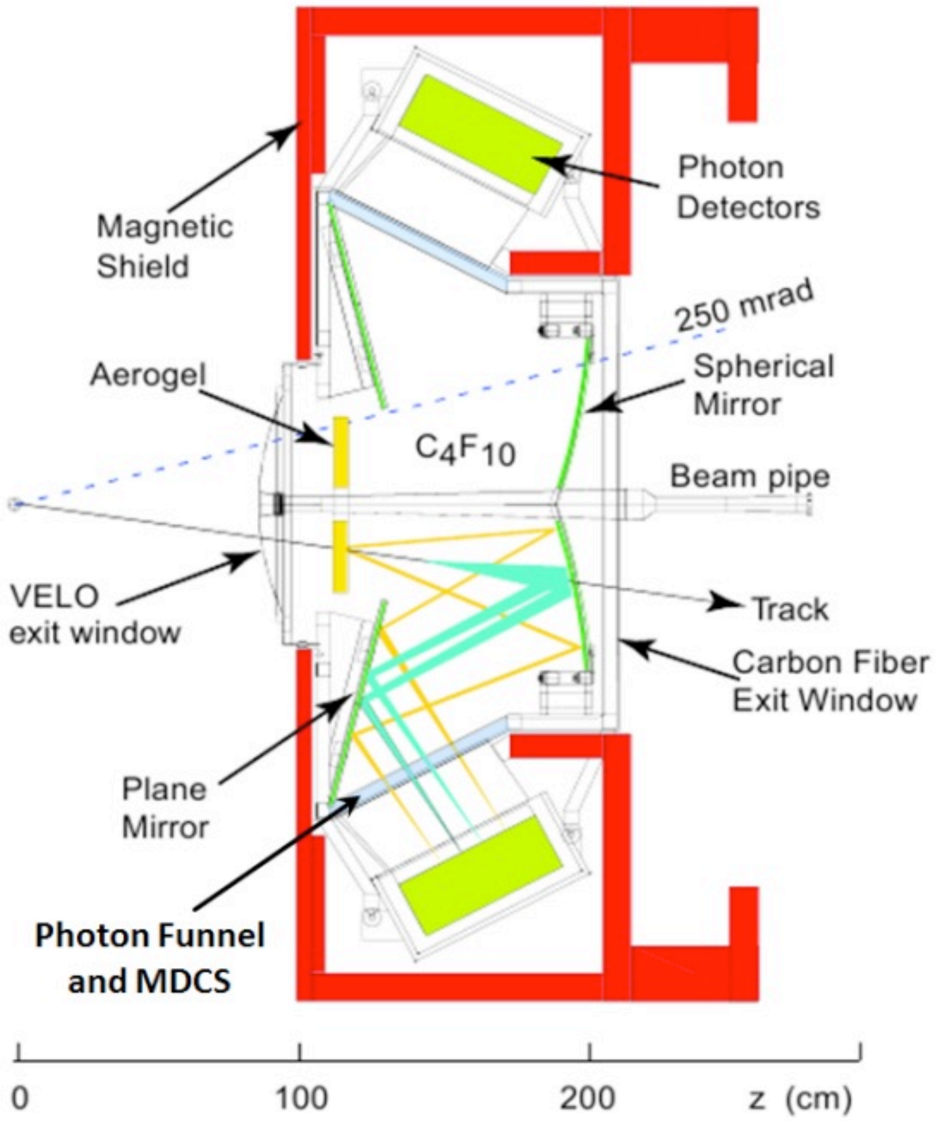
- Charged particles traversing a dielectric medium with refractive index n polarizes the molecules in the medium
- After the excitation the molecules return to an unpolarized start through the emission of photons
- If the velocity of the particle is greater than the speed of light in that medium $\boldsymbol{v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



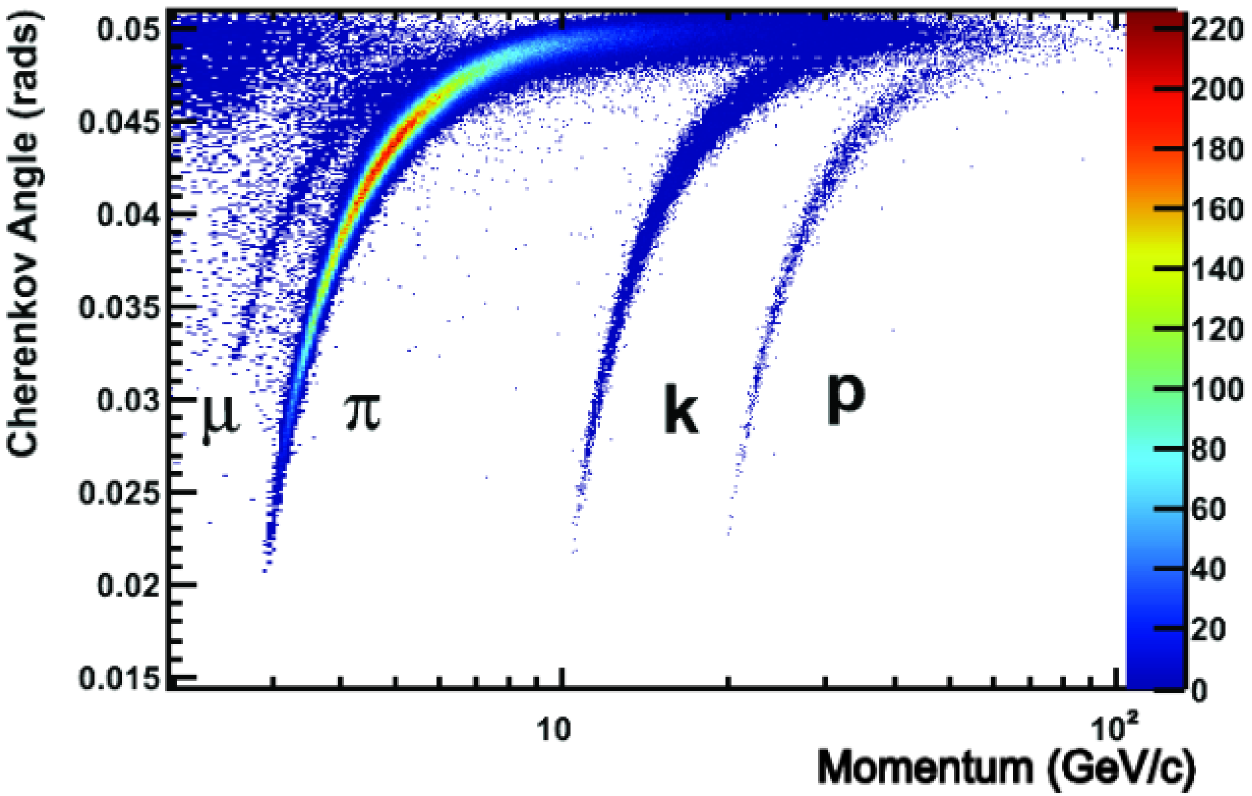
- Light produced at an angle θ
  - $\cos\theta = \frac{1}{\beta n}$
  - light emission if $\beta > 1/n$
  - $\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2+m^2}}$
  - $\boldsymbol{\Rightarrow m < p\sqrt{n^2 - 1}}$
- For a given p helps identifying the passing particles

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

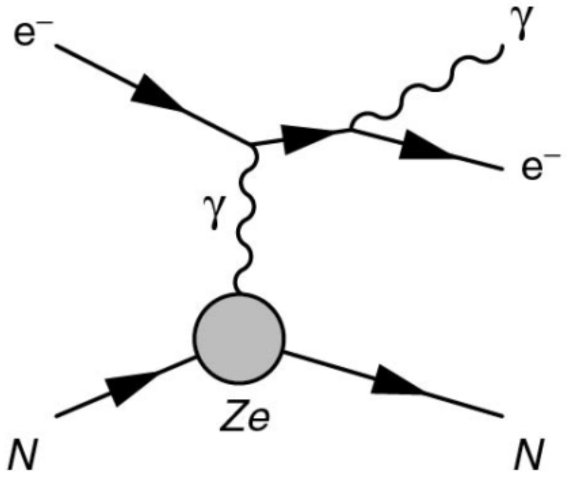


- Measure momentum p in the tracker, speed v in the RICH and derive the particle mass and therefore its type

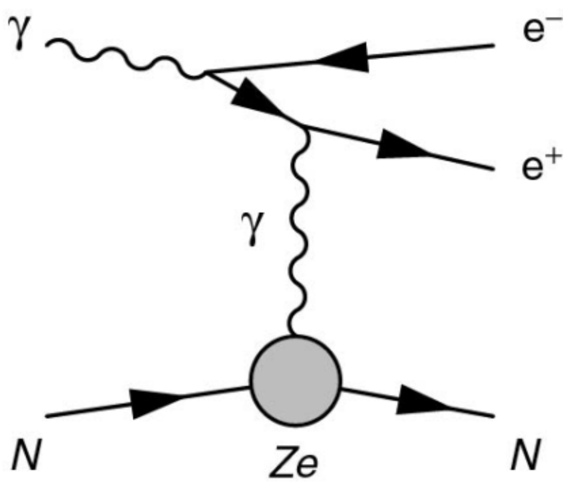
Bremsstrahlung and e^+e^- production

- Bremsstrahlung (breaking 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 $\propto 1/m^2_{particle}$ $\Longrightarrow$ 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 $\mathrm{E}_\gamma \sim 1$ MeV
  - e^+e^- pair production: dominant energy loss mechanism for photons with $E_\gamma > 10$ MeV

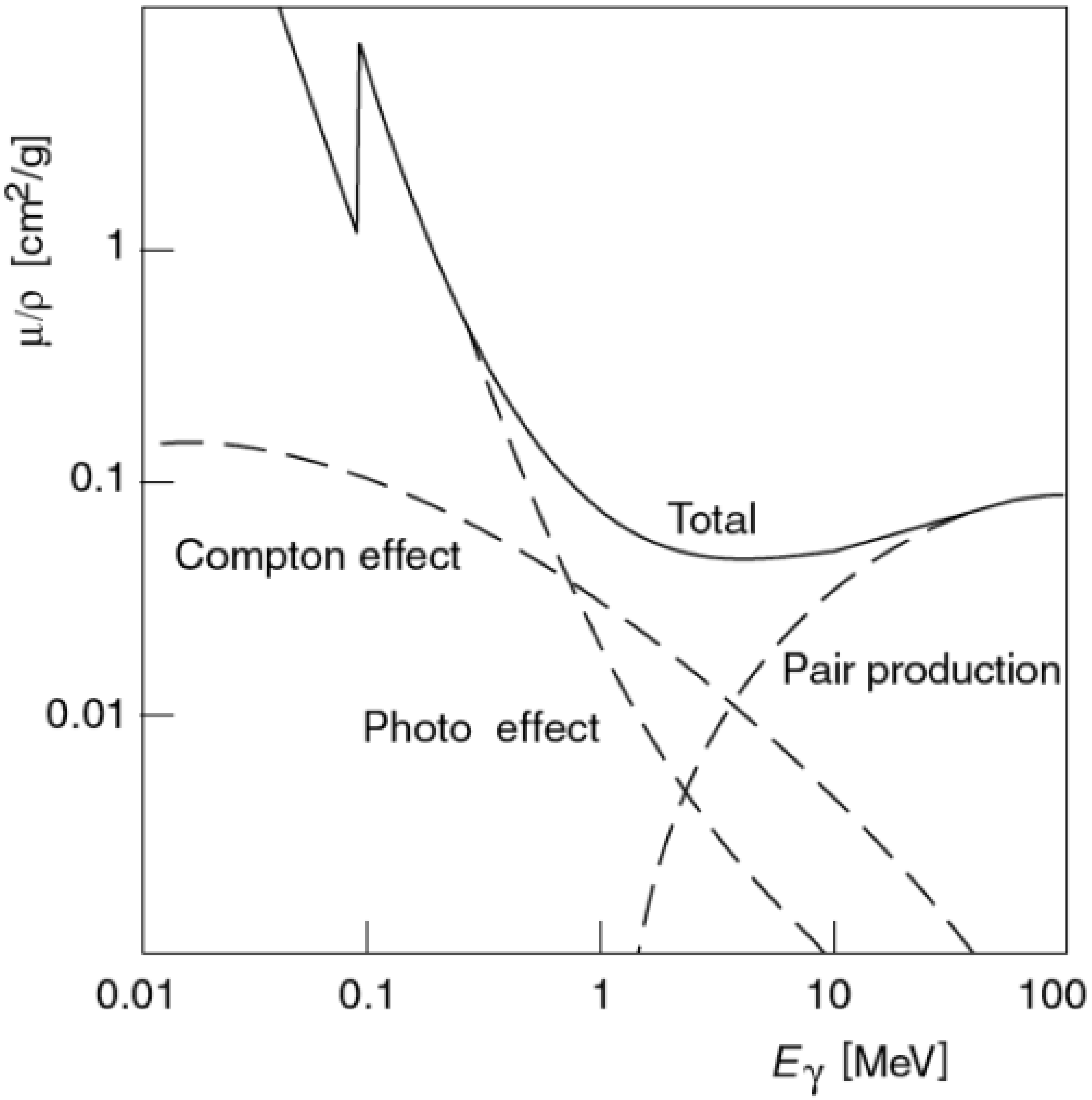
bremsstrahlung



e^+e^- pair production



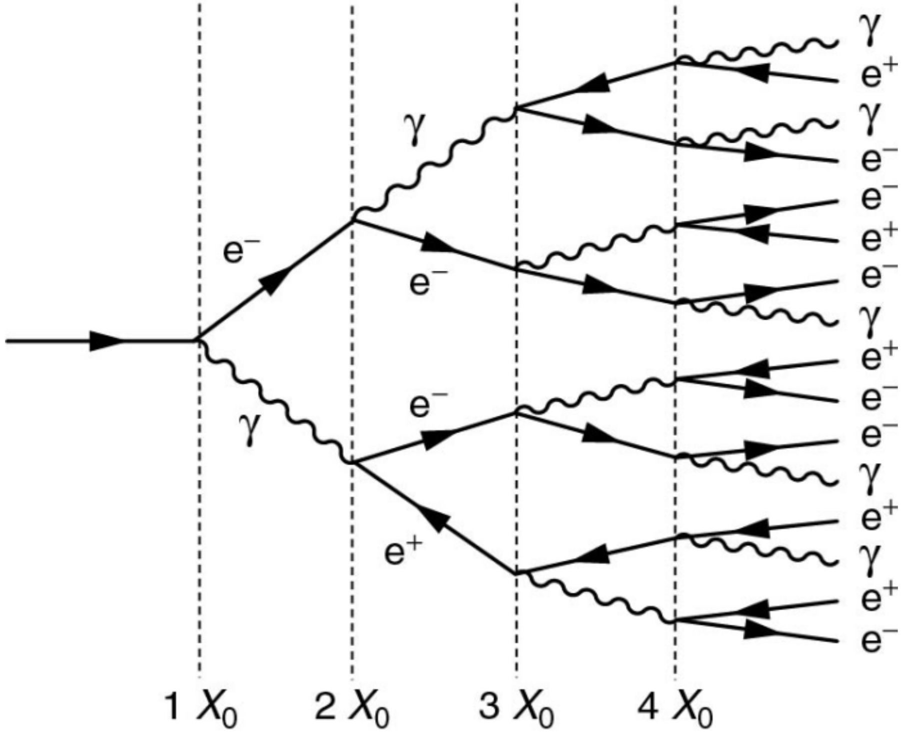
Interactions of photons with matter



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

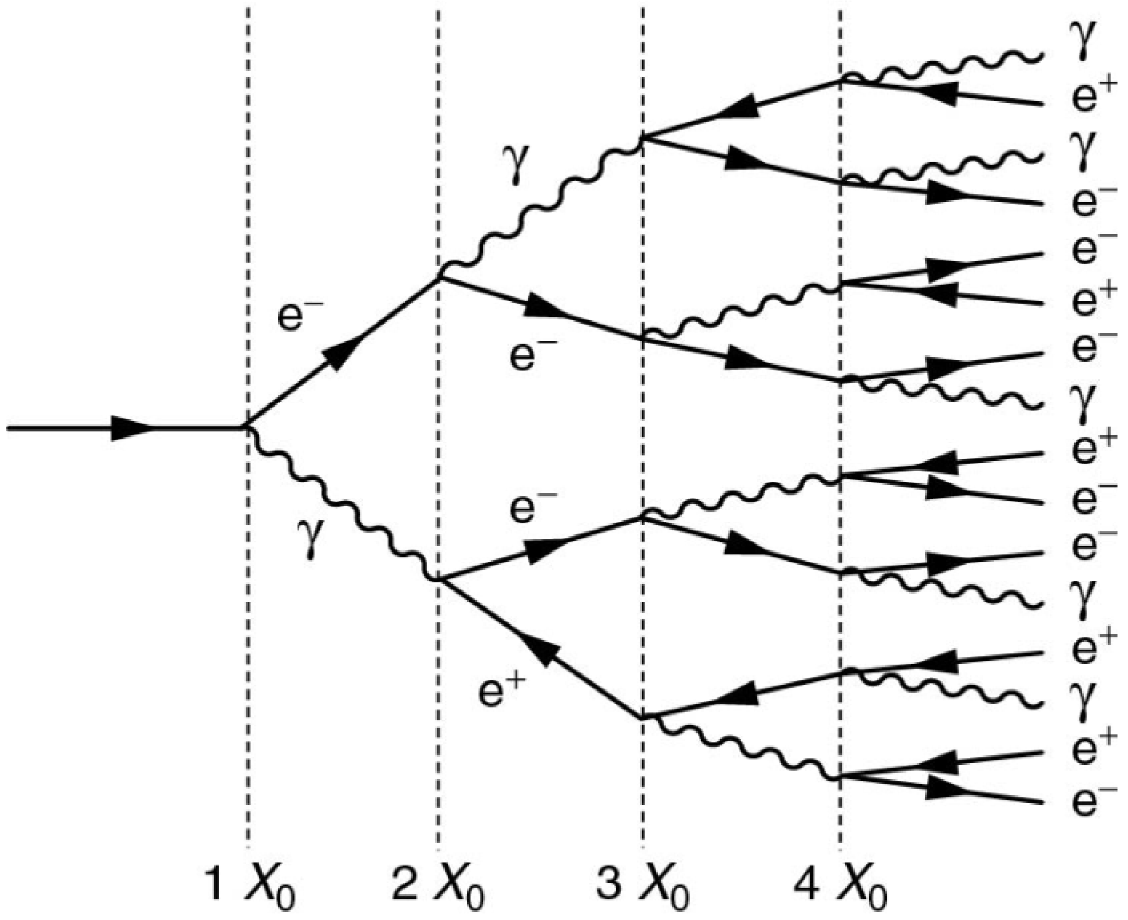
$$X_0 \approx \frac{1}{4\alpha n Z^2 r_e^2 \ln\left(\frac{287}{\sqrt{Z}}\right)},\ r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.8\times10^{-15}\ \mathrm{m}$$



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

Electromagnetic showers

- **Electromagnetic (EM) shower:** alternating bremsstrahlung and e^+e^- pair production process
- Number of particles ~ doubles every $X_0 \implies$ 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 $x_{\max} \sim 13\,X_0$
- $\implies x_{\max} = 7.28$ 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)

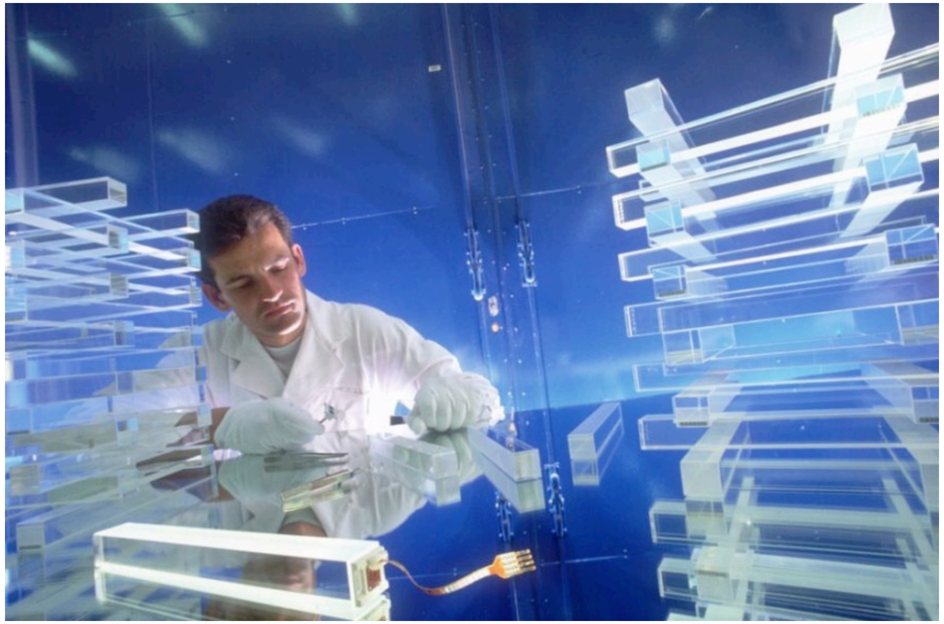
  - a: photoelectron statistics (sometimes called *stochastic* term), including effects due to the sampling fraction (how frequently we "sample" the shower profile)
  - b: electronics noise
  - c: calibration uncertainty and crystal non-uniformity

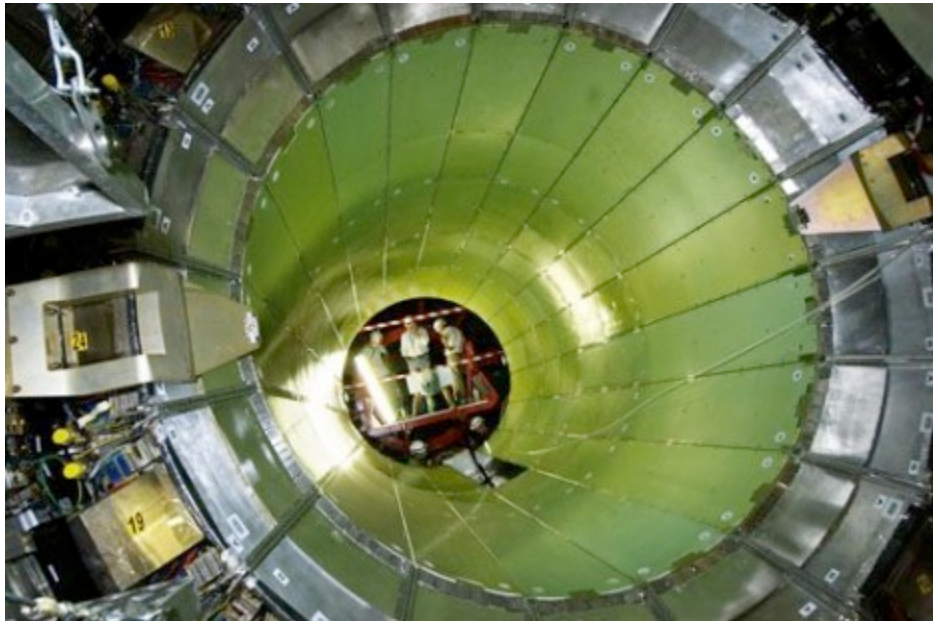
Types of electromagnetic calorimeters

- **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 $\Longrightarrow a = 2.7\%,\ b = 155\ \text{MeV}, c = 0.55\%$
- *Sampling calorimeters* have typical values of $a \sim 6 - 25\%$
  - example: LHCb ECAL $\Longrightarrow a = 10\%, c = 1\%$

Electromagnetic calorimeter of CMS





- Inorganic scintillation crystals (lead tungstate $PbWO_4$)
    - each crystal weighs 1.5 kg with a volume of a coffee cup
    - ECAL contains ~ 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

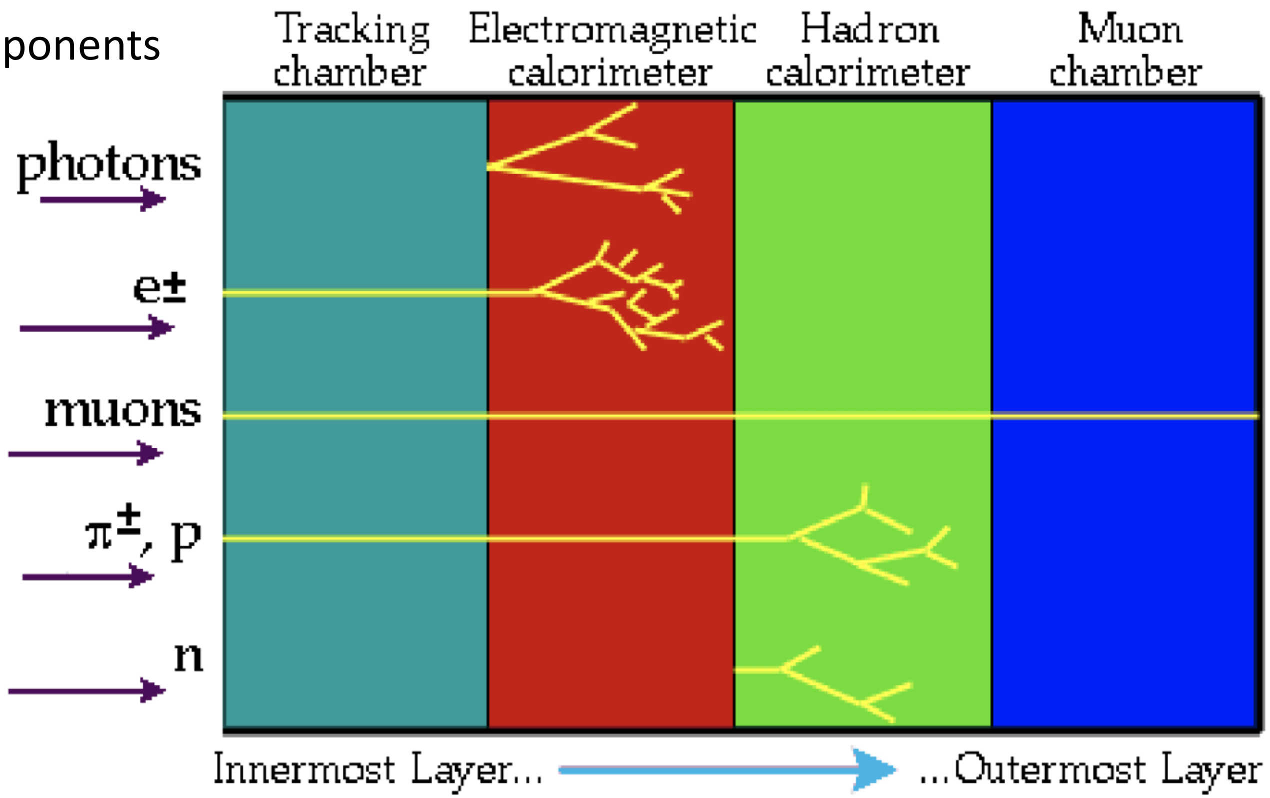
- ETH contribution
    - crystal R&D and procurement
    - development and tests of electronics components
    - integration of the readout electronics
    - detector control system
    - signal pulse reconstruction

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 $\boldsymbol{\lambda_I \approx 35\ \mathrm{g/cm^2}\ A^{1/3} \gg X_0}$
  - scintillation (scintillating crystals, liquid noble gas)
  - ionisation (liquid noble gas)
  - Cherenkov light (lead glass or heavy transparent crystals)
- Typical reaction: $p + \mathrm{nucleus} \rightarrow \pi^+ + \pi^- + \pi^0 + \ \ldots + \mathrm{nucleus}^*$
- Shower from a 100 GeV hadron extends $\sim$ 2 m longitudinally and $\sim$ 0.5 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 $\sigma_E/E \sim 50\%/\sqrt{E/\mathrm{GeV}}$ (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

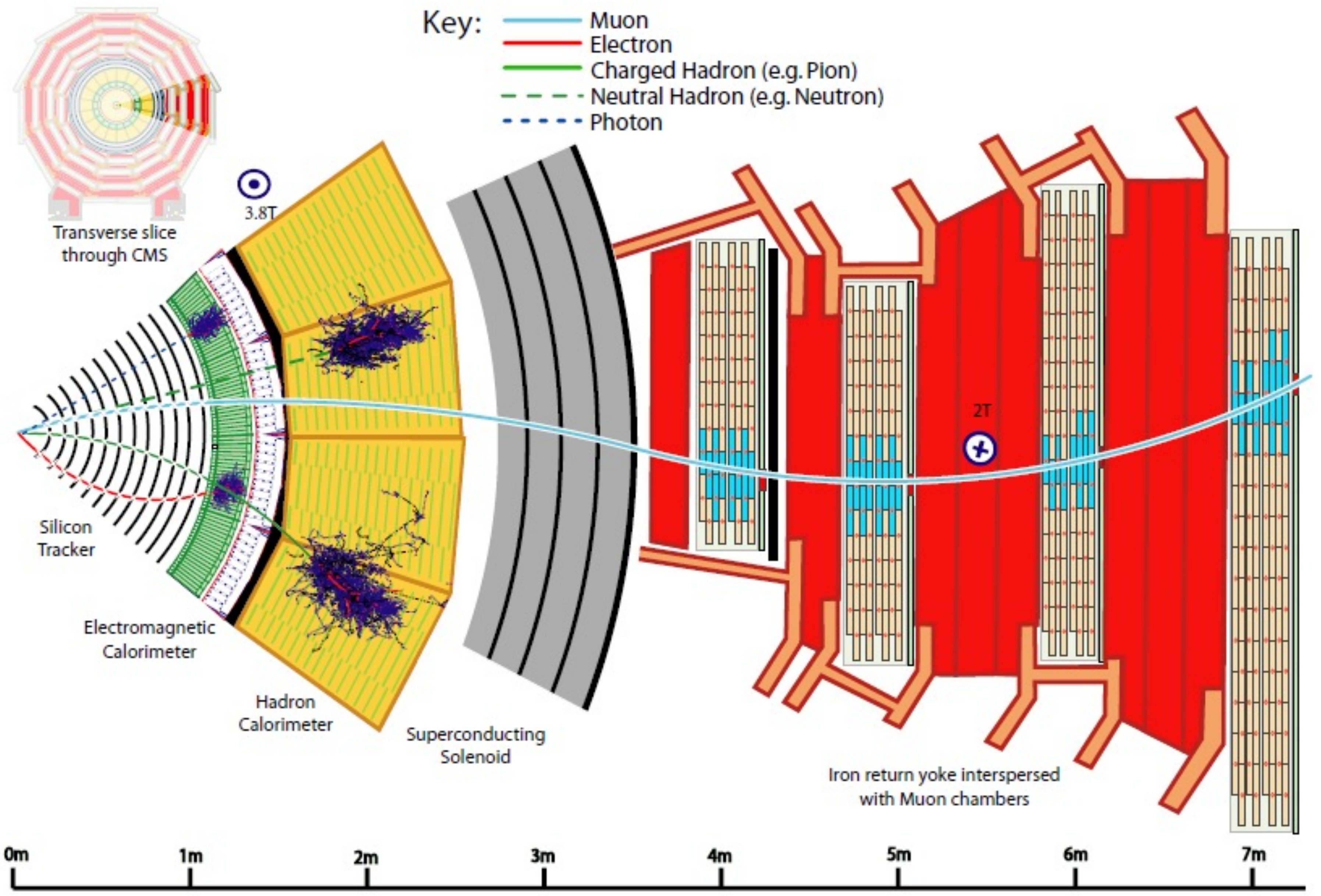
More information about particle detectors

- 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

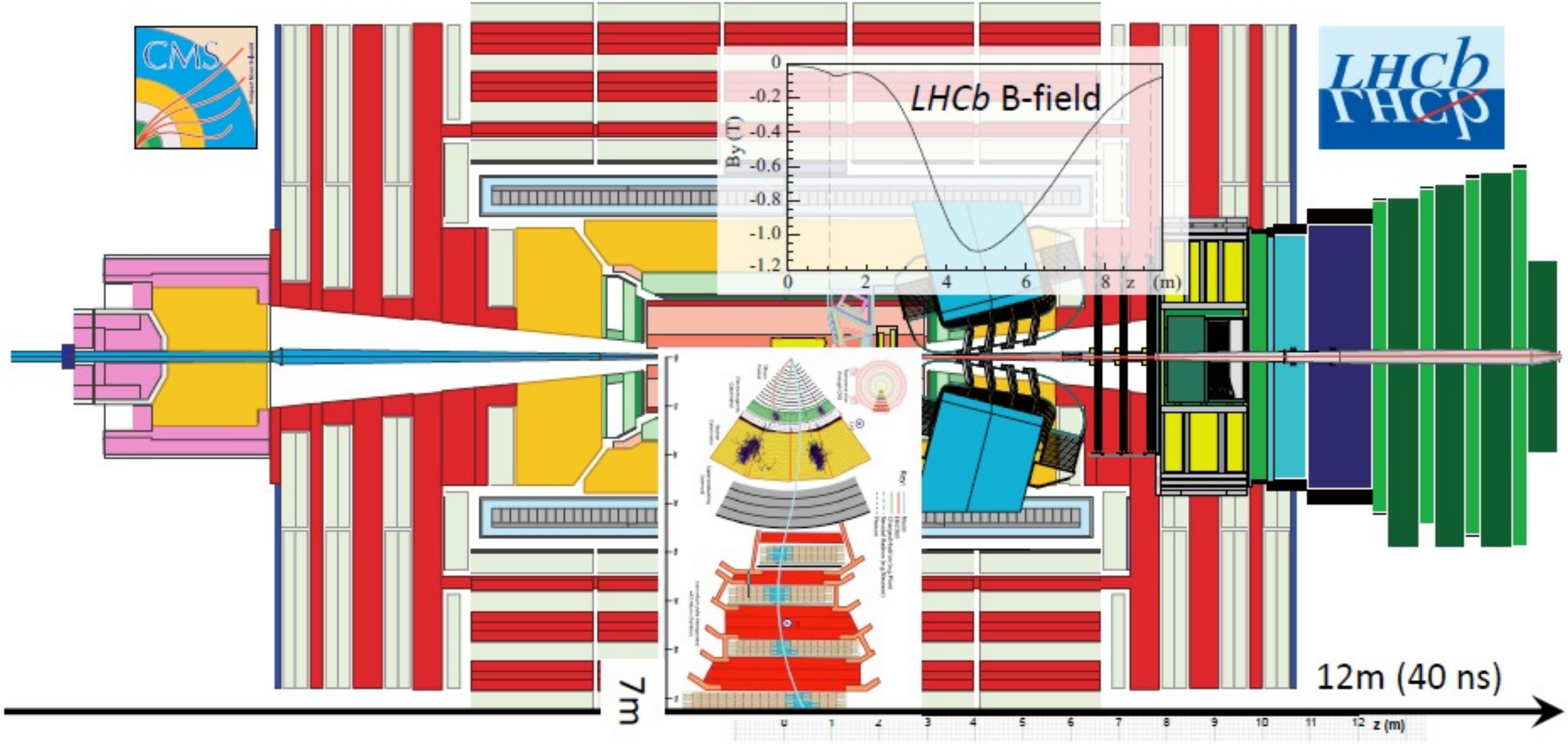
- A dedicated one-semester course given in the fall semester (now) by Guido Haefeli:
  - PHYS-440 – Particle Detection
  - https://edu.epfl.ch/coursebook/en/particle-detection-PHYS-440
  - everybody with interest in experimental particle physics is strongly encouraged to follow it!

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

Particles passing through detector: CMS

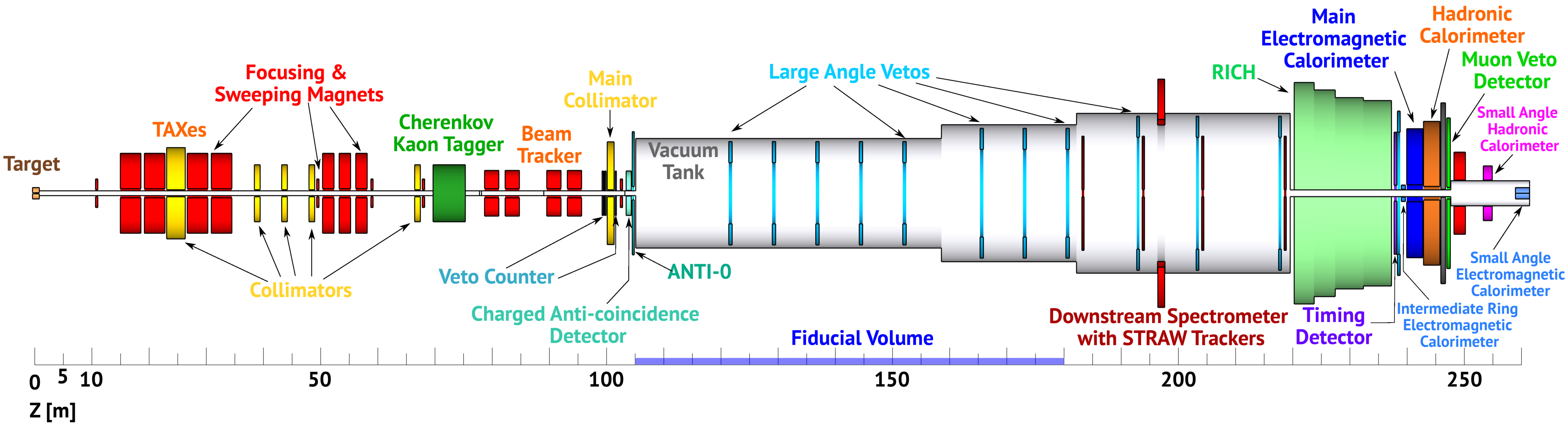


Detectors visualized



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

Detectors visualized

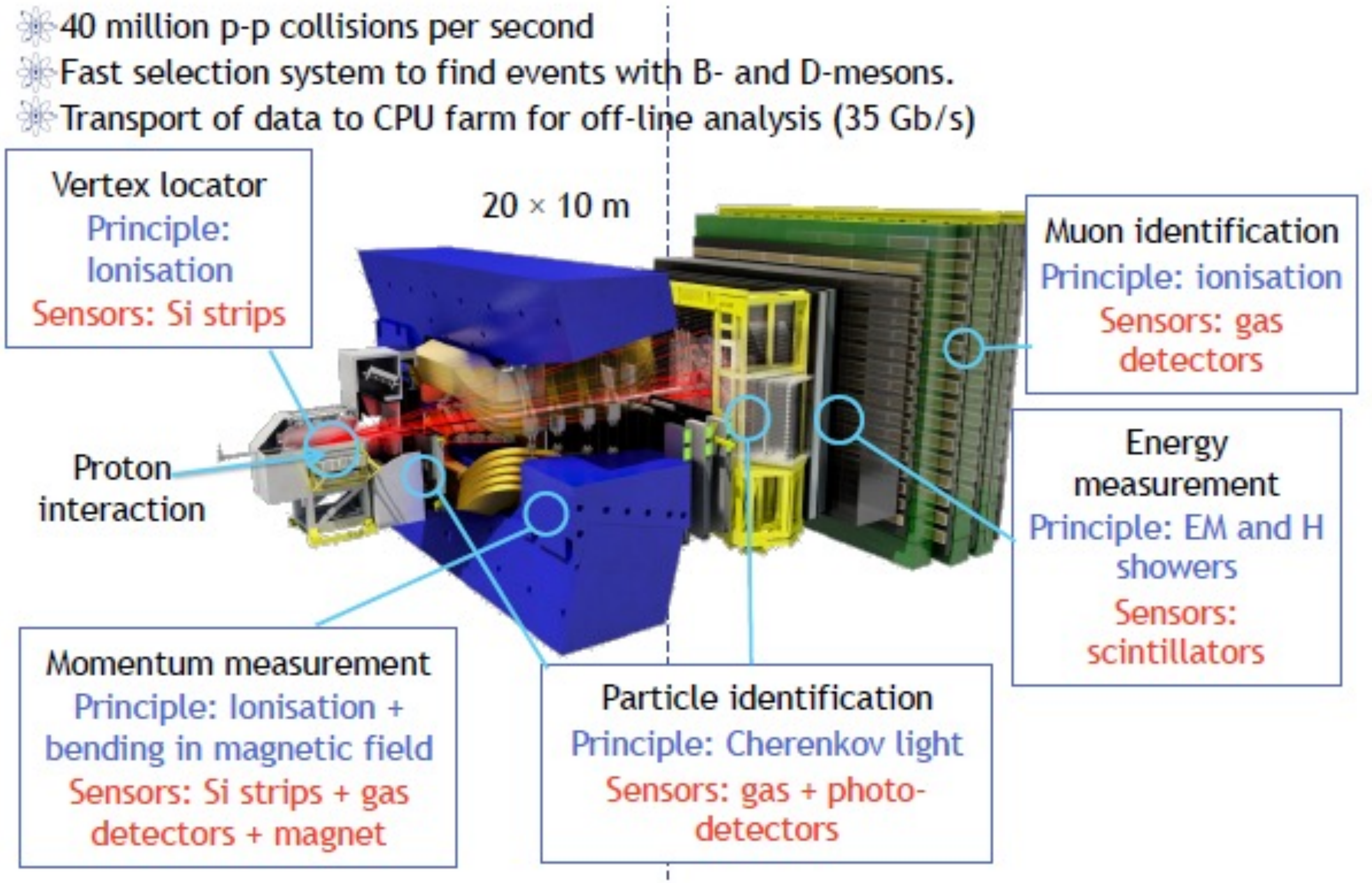


- Beam of 400 GeV protons hits the primary target
- Secondary unseparated beam of 75 GeV is created (mainly p, π^+, K^+) and guided to the fiducial decay volume
- Significantly boosted K meson ($\gamma \sim 150$) decays in flight in the fiducial decay volume $\sim 100 - 170$ m from the target
- 4π coverage 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