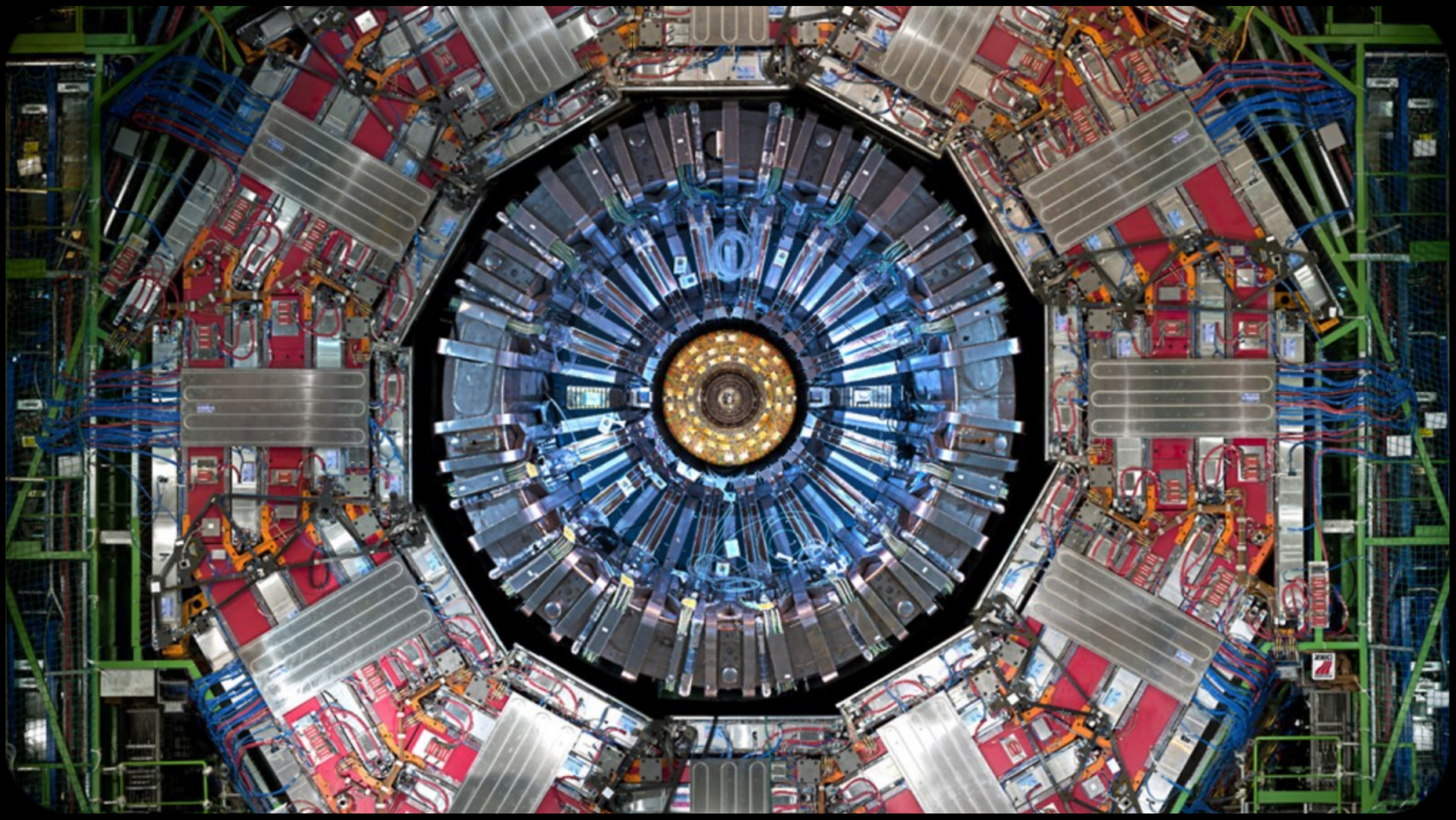
Interaction of particles with matter



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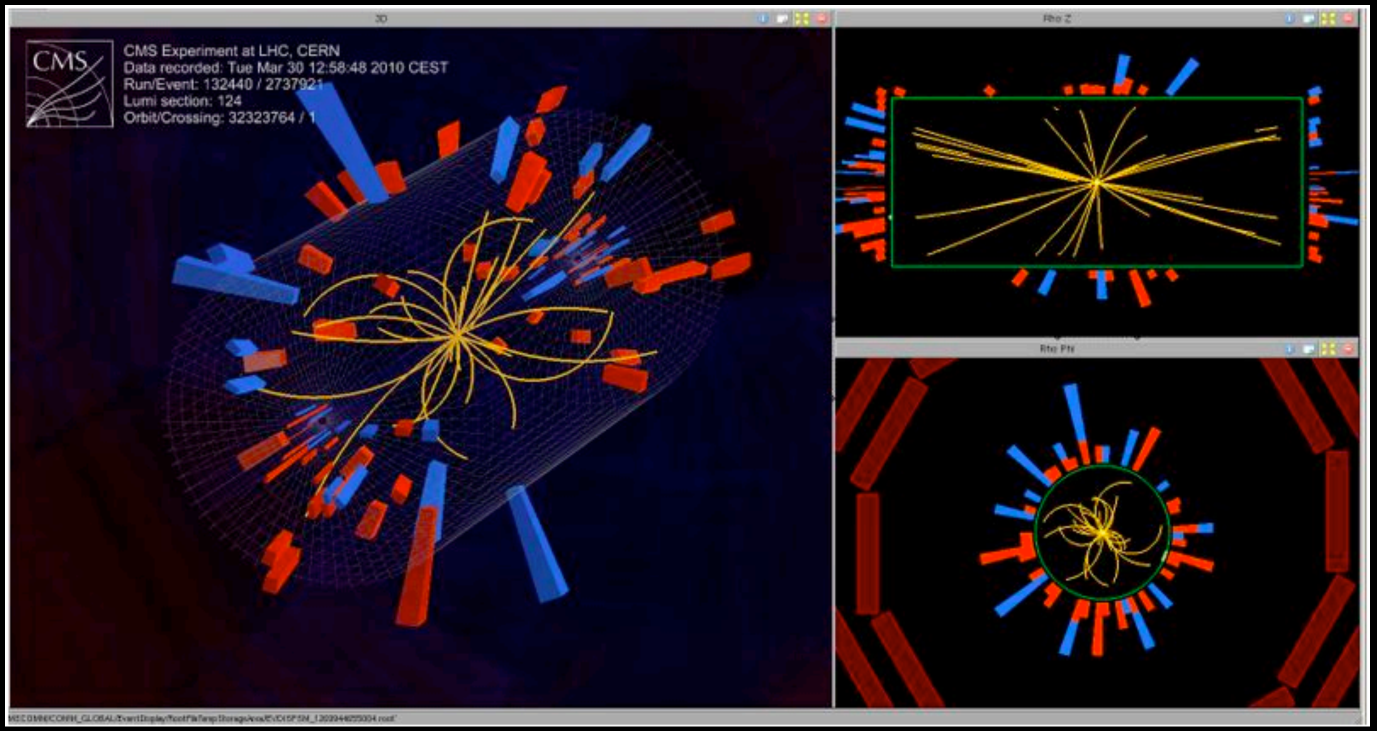
Interaction of particles with matter: categories

- The goal of (modern) particle physics experiments is to reconstruct and identify all particles produced in a collision



- Usage of various techniques reflected in the experimental setup
- Profit from knowledge of how particles interact with matter
  - Interaction of charged particles with matter
  - Electromagnetic interactions of electrons and photons
  - Strong interactions of charged and neutral hadrons

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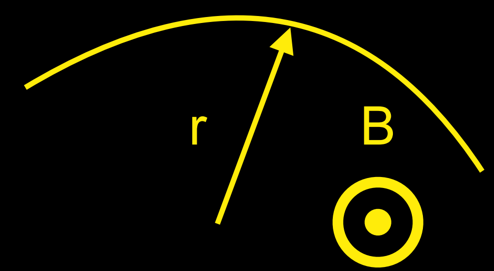
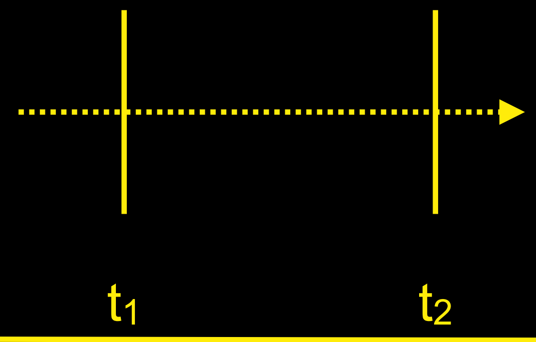
Detection and identification of particles

- Detection: did a particle cross a given area?
- Identification: what kind of particle crossed a given area?
  - Requires measurement of the mass and the charge of a particle
- In most cases detectors are placed inside a magnetic field
  - Measure the momentum of a particle through its curvature



$$r = \frac{p}{ZeB} \propto \frac{p}{Z} = \frac{\gamma m \beta c}{Z}$$

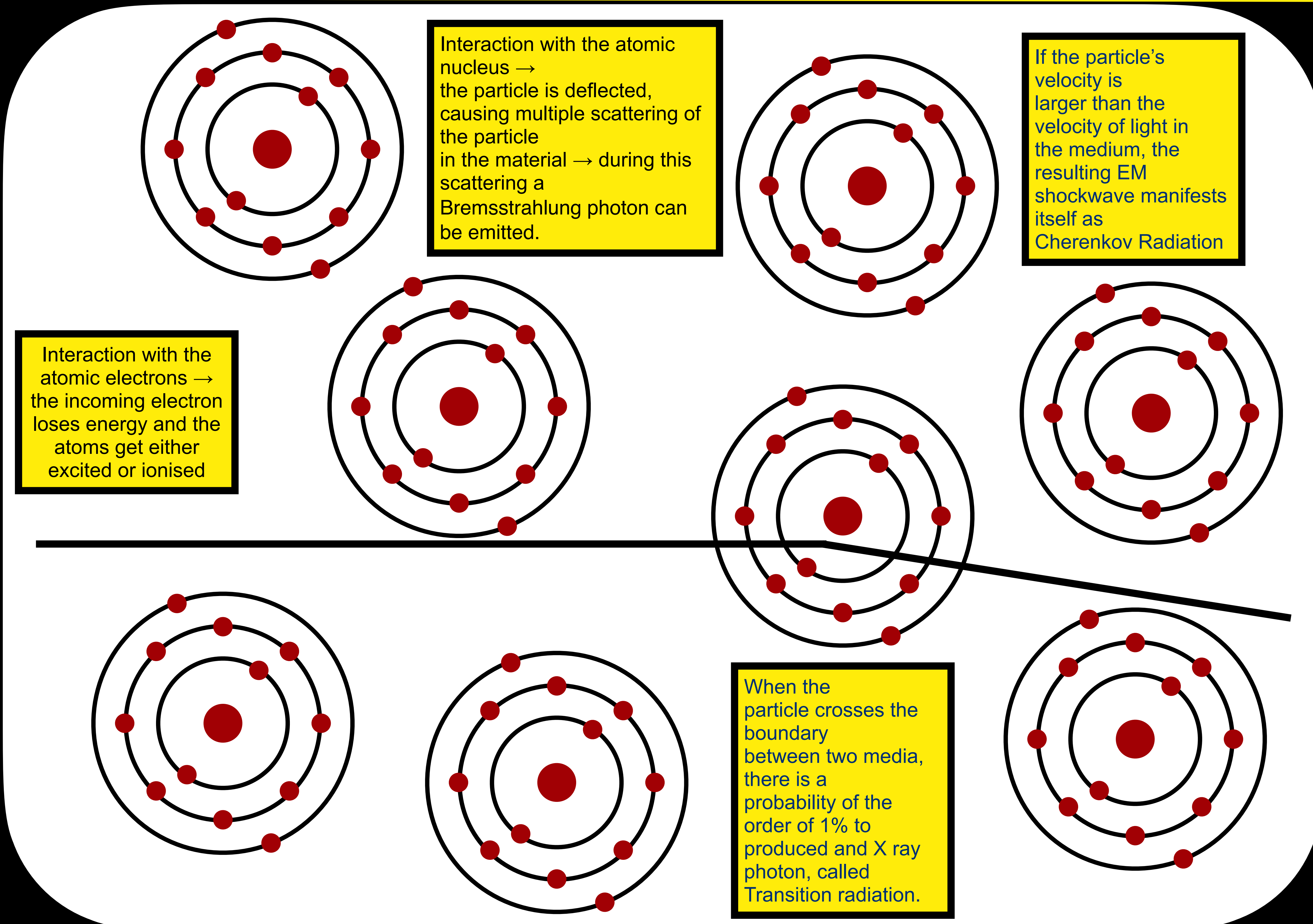
- Measure velocity through the time-of-flight technique



$$\Delta t = \frac{1}{\beta}$$

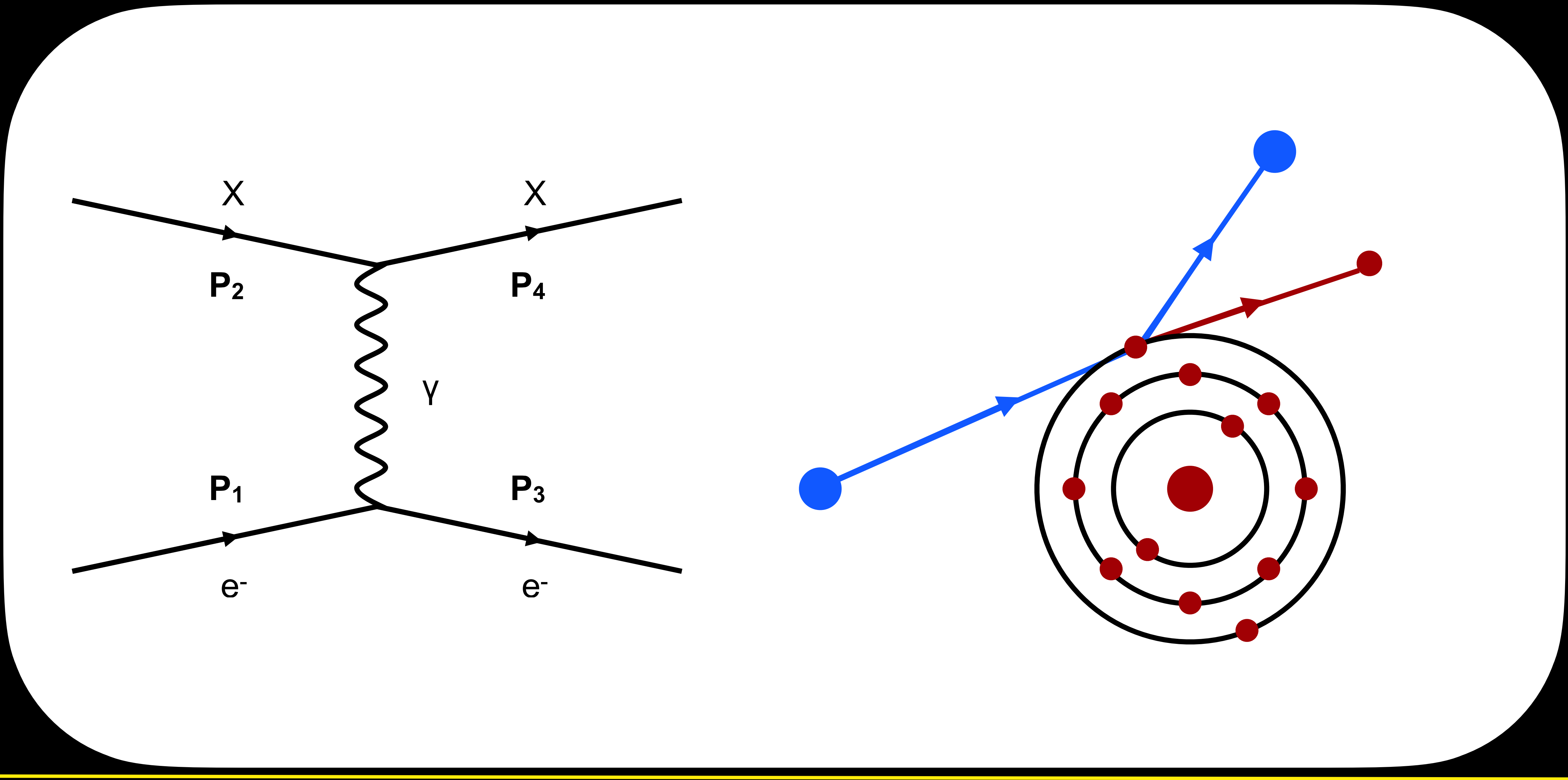
Interaction and detection of charged particles

Interaction of charged particles with matter: overview



Interaction of charged particles with matter (1)

- Relativistic charged particle passes through a medium
  - interacts electromagnetically with the atomic electrons
  - loses energy through ionisation of the atoms



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Interaction of charged particles with matter (2)

✓ Bethe-Bloch equation:

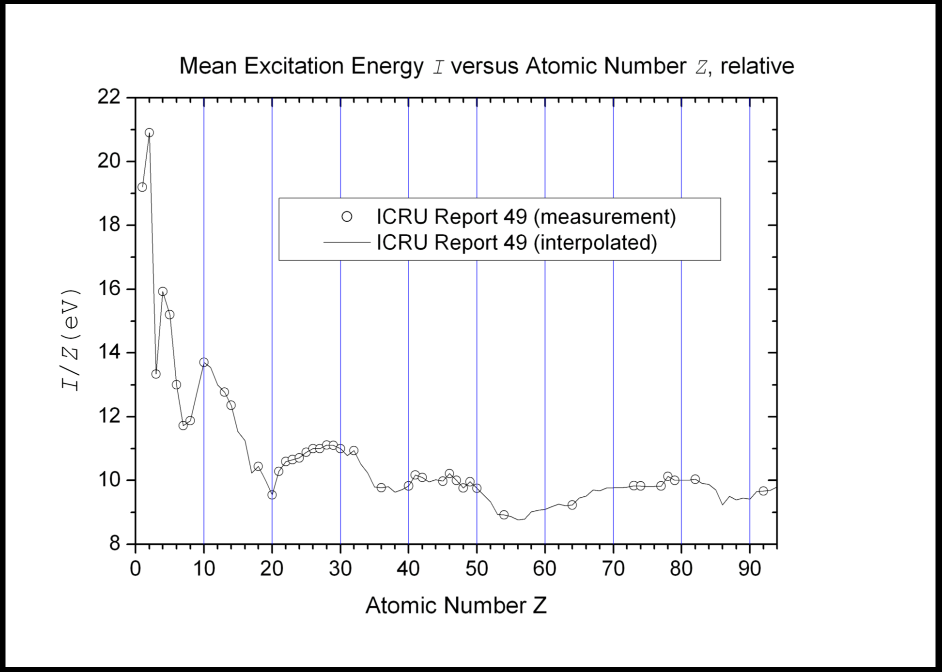
$$\frac{dE}{dx} \approx -4\pi\hbar^2 c^2 \alpha^2 \frac{nZ}{m_e v^2}\left[\ln\left(\frac{2\beta^2\gamma^2 c^2 m_e}{I_e}\right) - \beta^2\right]$$

- Describes the ionisation energy loss per unit length traversed for a singly charged particle with velocity v = βc traversing a medium

- I_e is the effective ionisation potential of the material averaged over all atomic electrons, which is very approximately given by I_e ~10Z eV

- Z is the atomic number of the medium

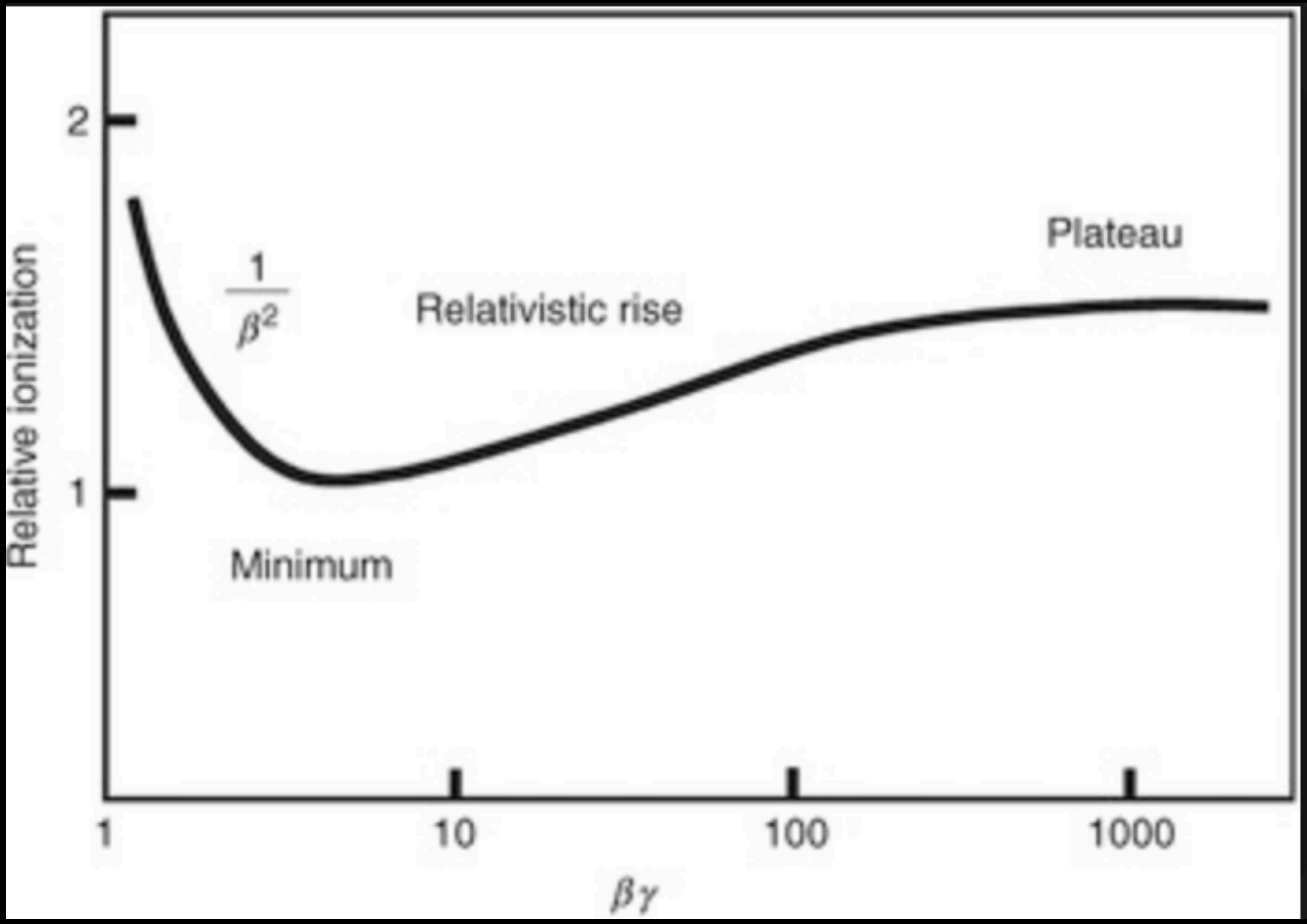
- n is the number density of the medium



Interaction of charged particles with matter (3)

For larger values of momentum the energy loss goes as a function of $\ln(\beta\gamma)^2$

At small values of momenta dE/dx falls as $1/\beta^2$



Reaching a plateau at very large values of $\beta\gamma$

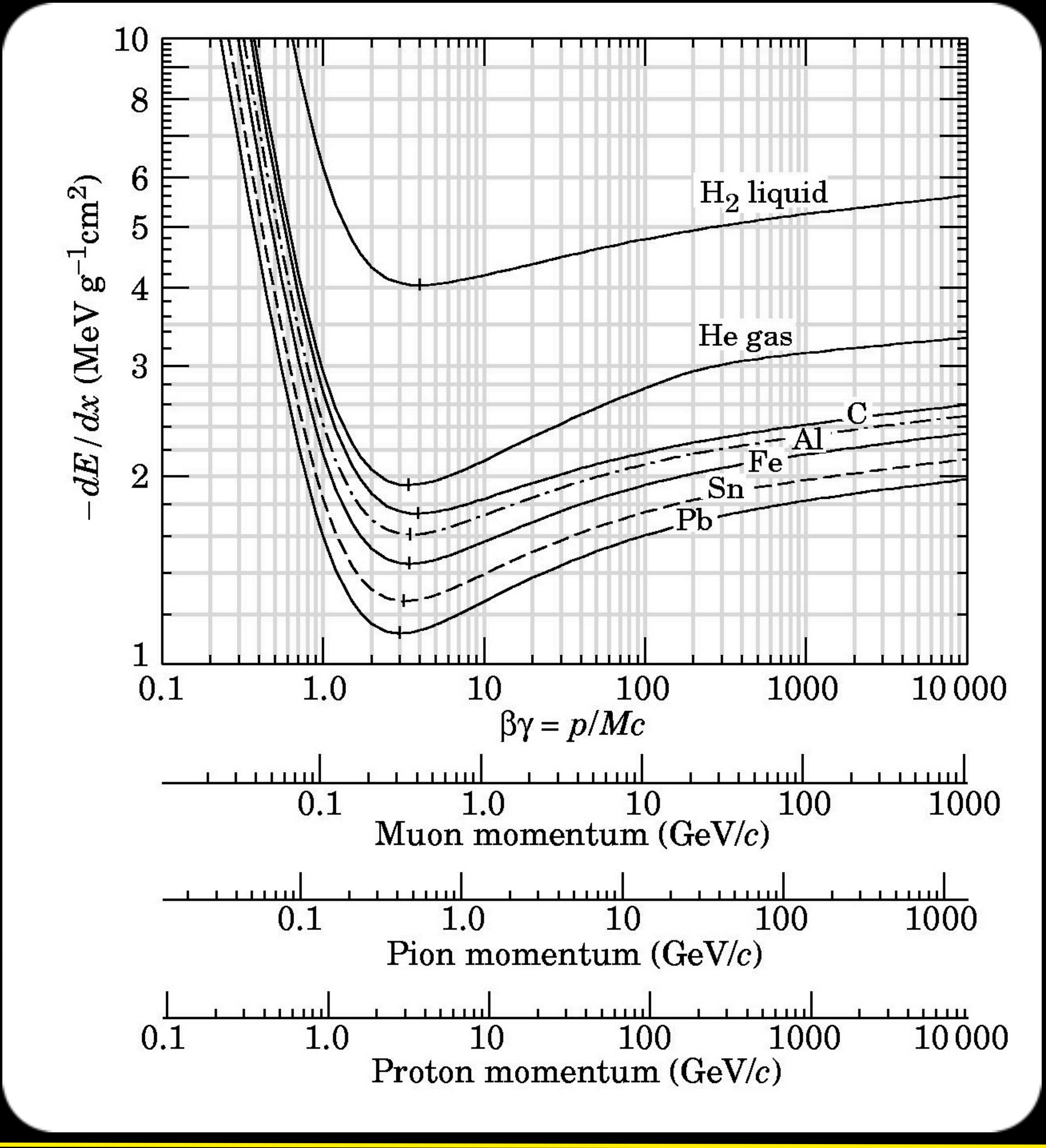
Minimum energy loss at around $\beta\gamma\sim 3$-4

Interaction of charged particles with matter (4)

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

- For a given material the rate of the ionisation energy loss of a charged particle is a function of its velocity

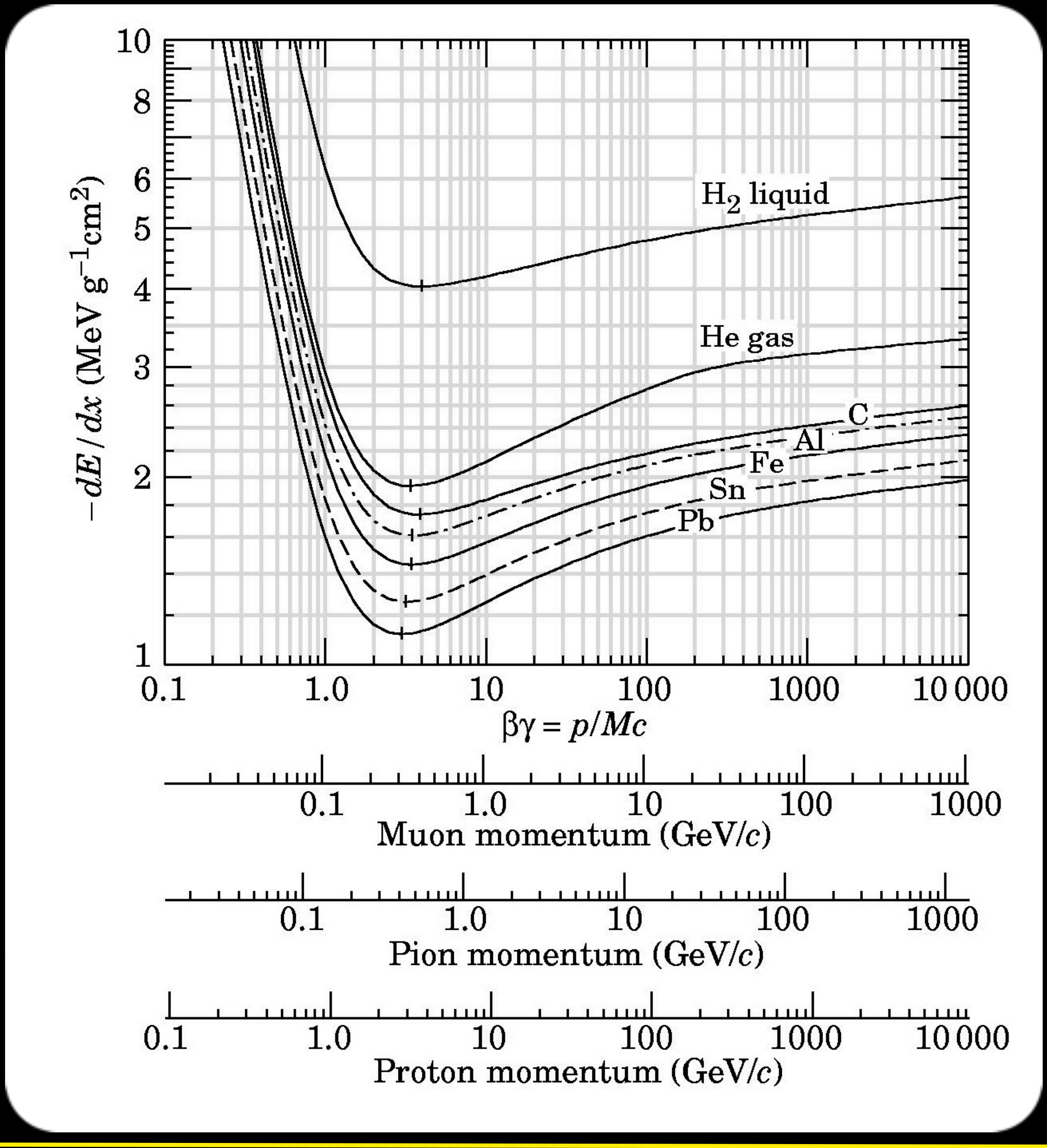
  - A “slow” particle (i.e. low momentum) loses energy as $1/v^2$
    - Slow particles lose the maximum energy
  - For a “fast” particle (i.e. large momentum) the energy loss depends logarithmically on $(\beta\gamma)^2$
    - Leads to a rise of energy loss known as the relativistic rise



Interaction of charged particles with matter (5)

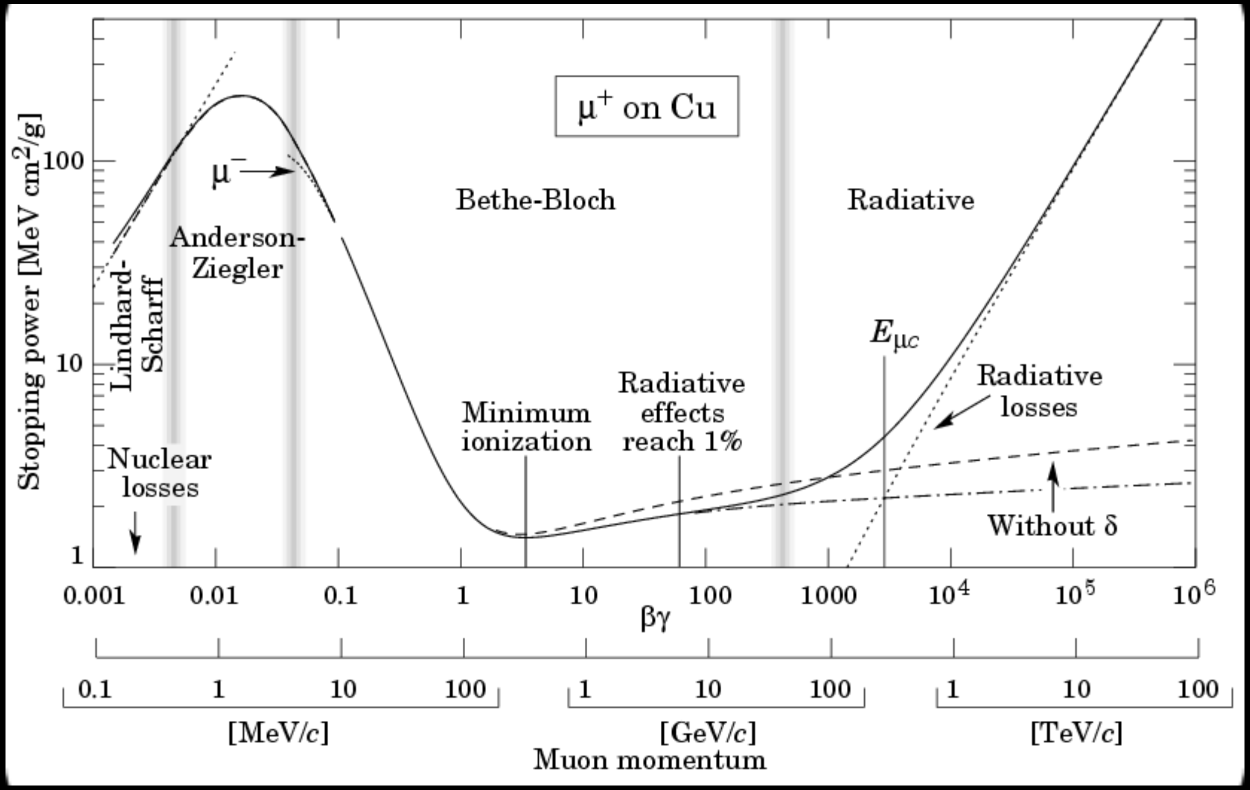
$$\frac{dE}{dx} \approx -4\pi\hbar^2 c^2 \alpha^2 \frac{nZ}{m_e v^2}\left[\ln\left(\frac{2\beta^2\gamma^2 c^2 m_e}{I_e}\right) - \beta^2\right]$$

- ✓ The energy loss for a given velocity is similar for various materials
  - Decreases slowly with increasing atomic number (Z)
- ✓ Particles with βγ~3 are called minimum ionisation particles

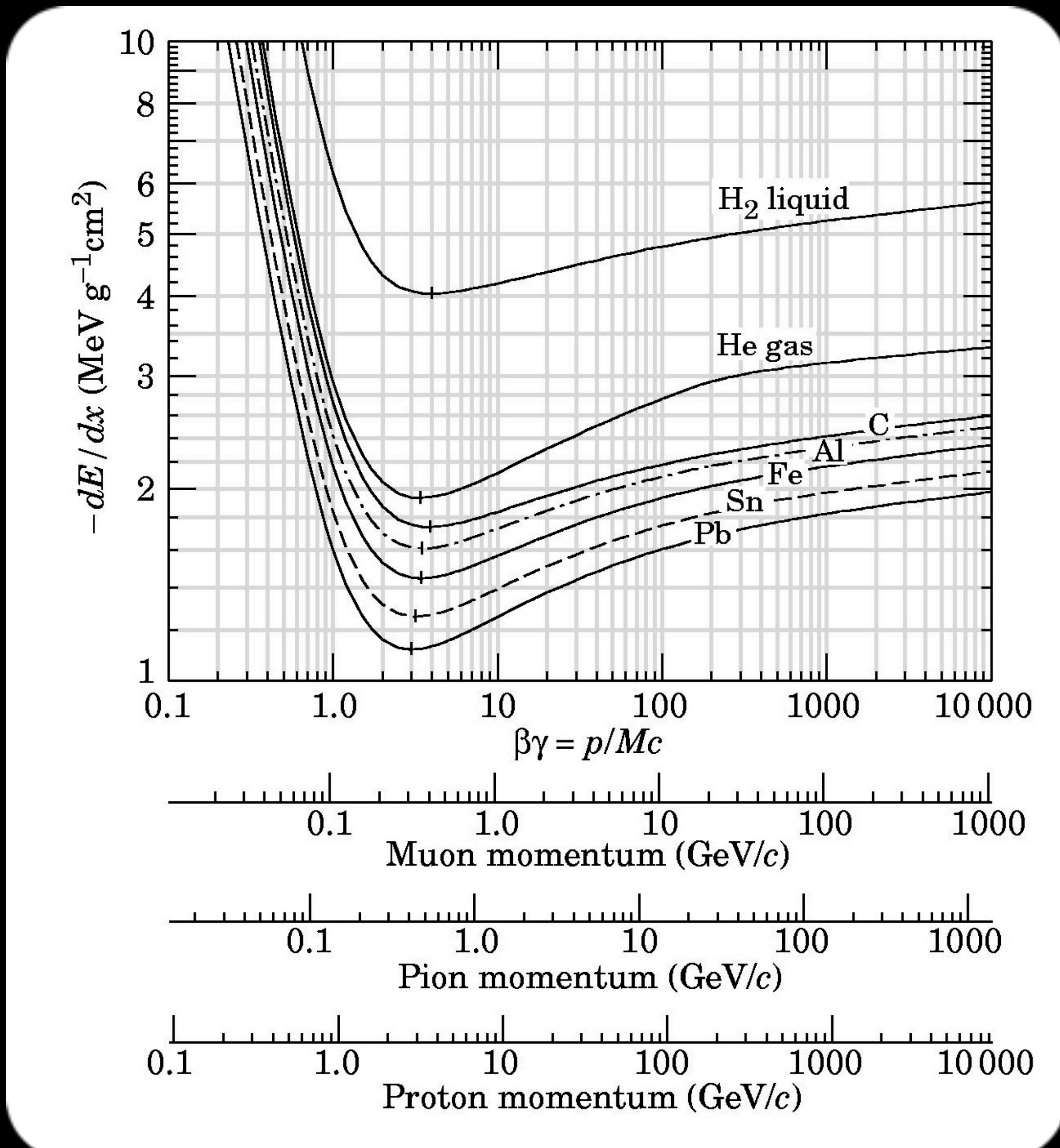


Interaction of charged particles with matter (6)

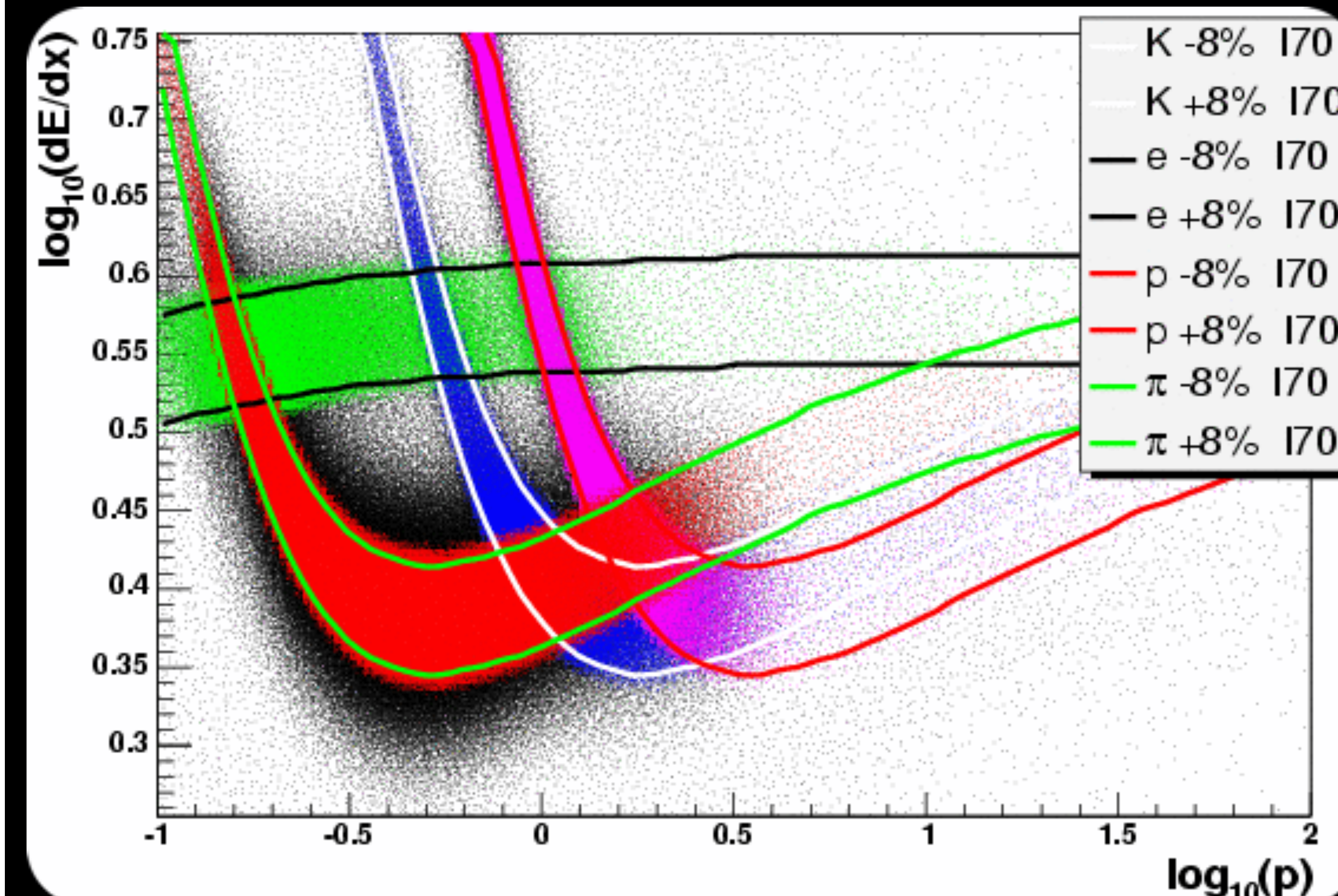
- Depending on the particle type, other energy-loss mechanisms maybe present
- As an example for muons with energies below 100 GeV, ionisation is the dominant energy loss
  - a muon travels significant distances even in dense materials like iron
    - As an example, a muon with energy of around 10 GeV loses approximately 13 MeV/cm in iron and thus will be able to travel for several meters
    - As a result, the muons produced in collisions of particles in modern particle accelerators are very penetrating particles, they usually traverse the entire detector and leave a trail of ionisation.
      - This is the feature that can be exploited to identify muons experimentally.



Interaction of charged particles with matter (7)



STAR Time Projection Chamber (TPC)



- ✓ The energy loss as a function of momentum p=mcβγ is dependent on the particle mass
- ✓ By measuring the particle momentum (deflection in a magnetic field) and the energy loss one gets the mass of the particle, i.e. particle ID

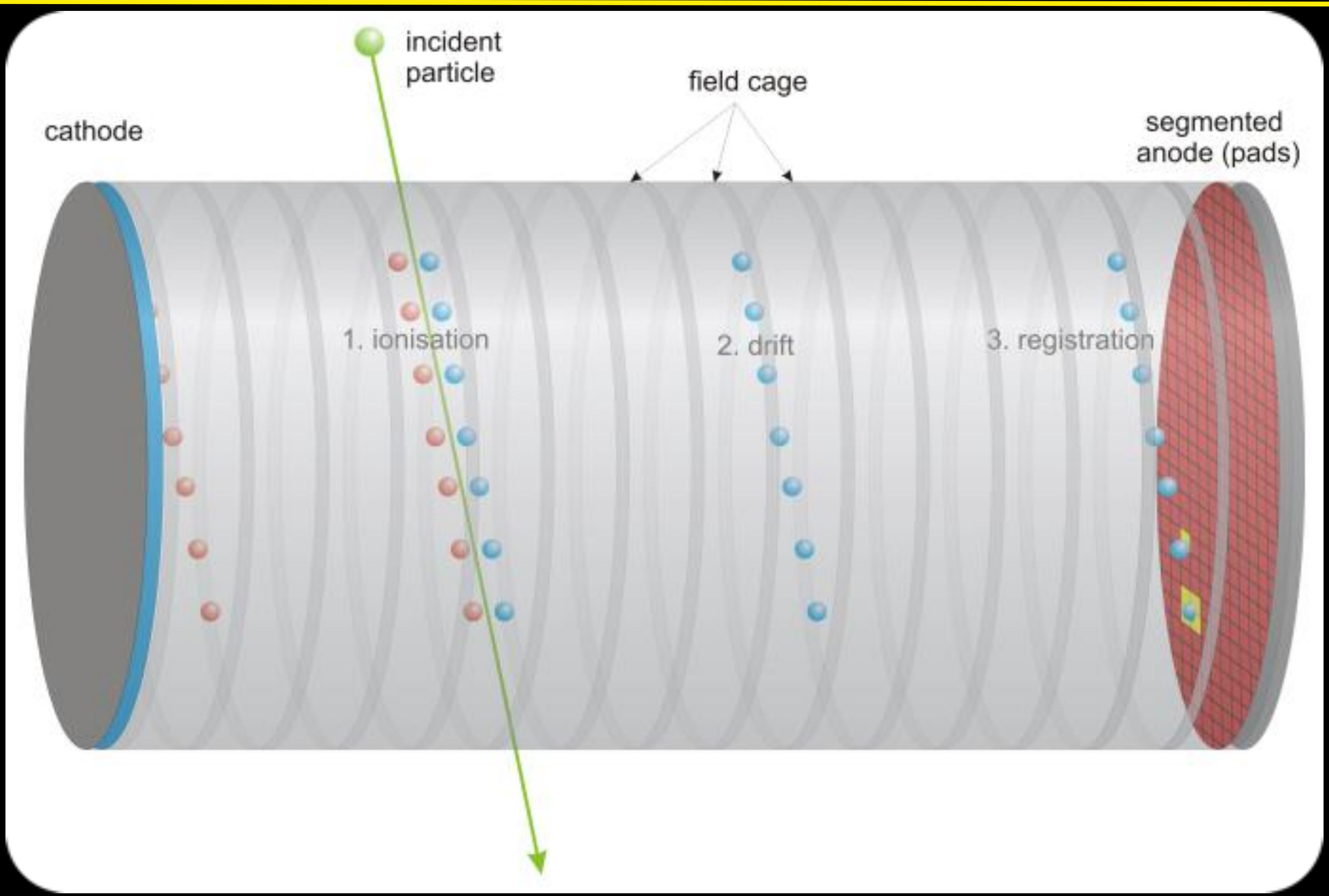
Detection of charged particles

- The detection and measurement of momenta of charged particles is an essential aspect of every large particle physics experiment
- Regardless of the medium, through which a charged particle travels, it leaves a trail of ionised atoms and liberated electrons
- By detecting this ionisation it is possible to reconstruct the trajectory of a charged particle.
- There are two categories of tracking detectors used in modern experiments
  - large gaseous detectors such as the TPC discussed before, where the liberated electrons are drifted in strong electric fields towards the sense wires where a signal is detected,
  - detectors using semiconductor technology such as silicon pixels or strips.

Detection of charged particles: Gaseous detectors (1)

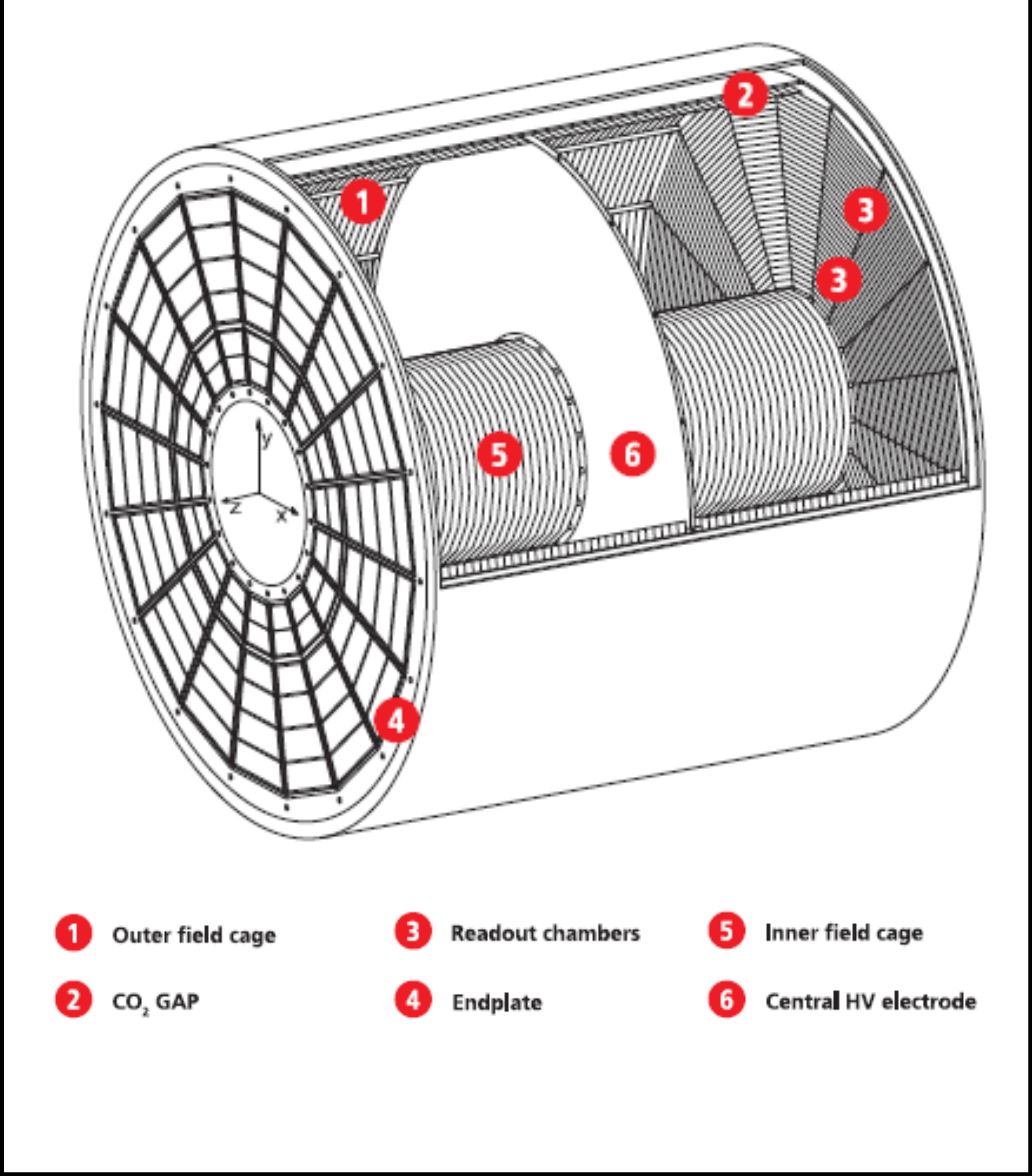
- One of the most used detectors in particle physics
- Most common design: cylindrical chamber with multi-wire proportional chambers (MWPC) as endplates
- Along its length, the chamber is divided into halves by means of a central high-voltage electrode disc
  - establishes an electric field between the centre and the end plates.
- A magnetic field is often applied along the length of the cylinder, parallel to the electric field, in order to minimise the diffusion of the electrons coming from the ionisation of the gas
- Passing through the detector gas, a particle will produce primary ionisation along its track
- The z coordinate (along the cylinder axis) is determined by measuring the drift time from the ionisation event to the MWPC at the end
- The MWPC at the end is arranged with anode wires which provides information on the radial coordinate (r)
- To obtain the azimuthal direction, each cathode plane is divided into strips along the radial direction

Detection of charged particles: Gaseous detectors (2)



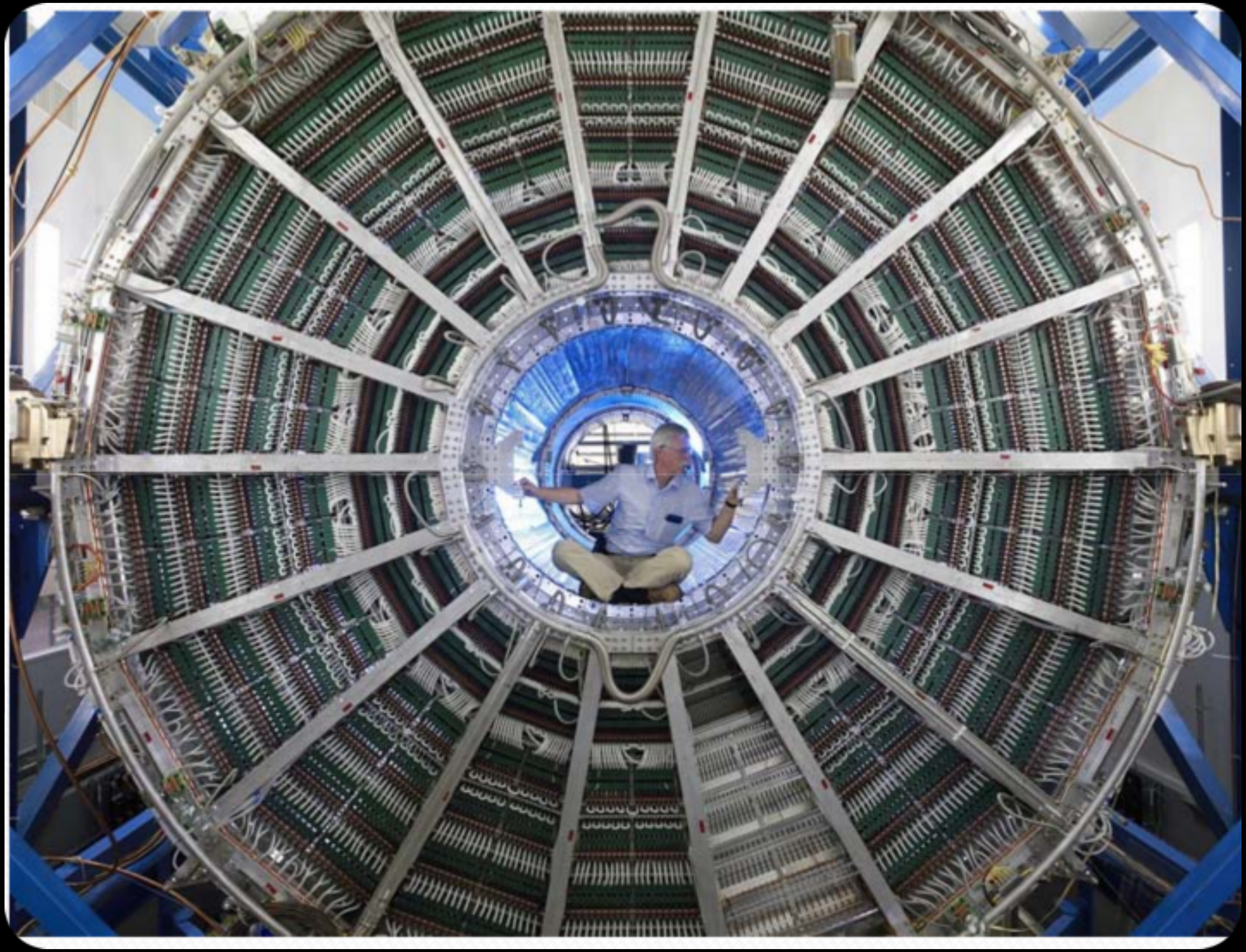
- Charged particle traversing the gas volume of the TPC ionizes the atoms of the gas mixture along its trajectory → create electrons
- An electric field is applied between the endplates of the chamber (anode/cathode) → released electrons drift in this field towards the anode.
- Additionally, a high magnetic field parallel to the electric field is used to ”bend” the trajectory of the particle on a spiral track due to the Lorentz force.
  - This gives the possibility to calculate the momentum of the particle from the knowledge of the curvature and the B-field.

Detection of charged particles: Gaseous detectors (3)

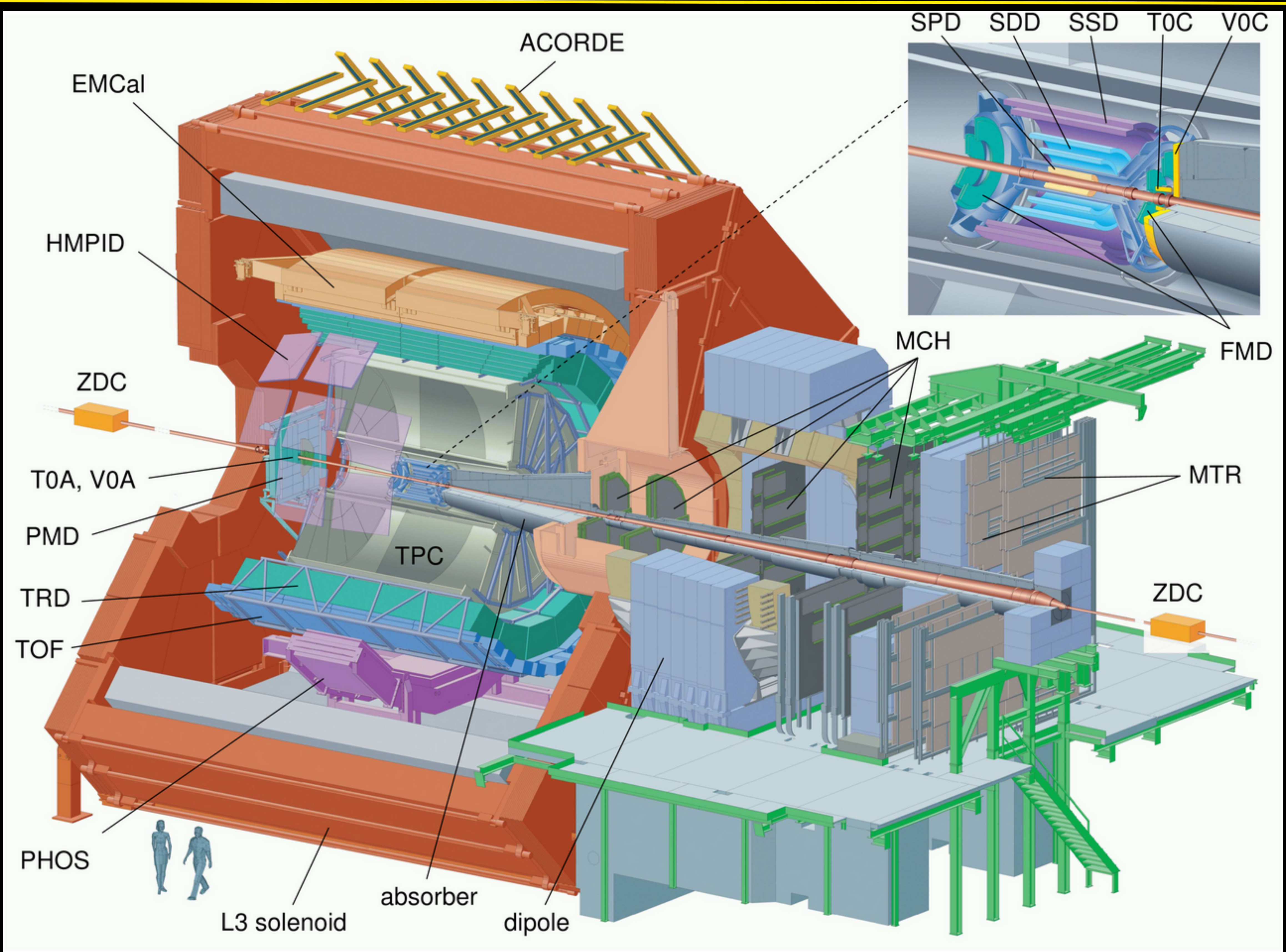


Detection of charged particles: Gaseous detectors (4)

The TPC of the ALICE experiment@LHC



ALICE@LHC



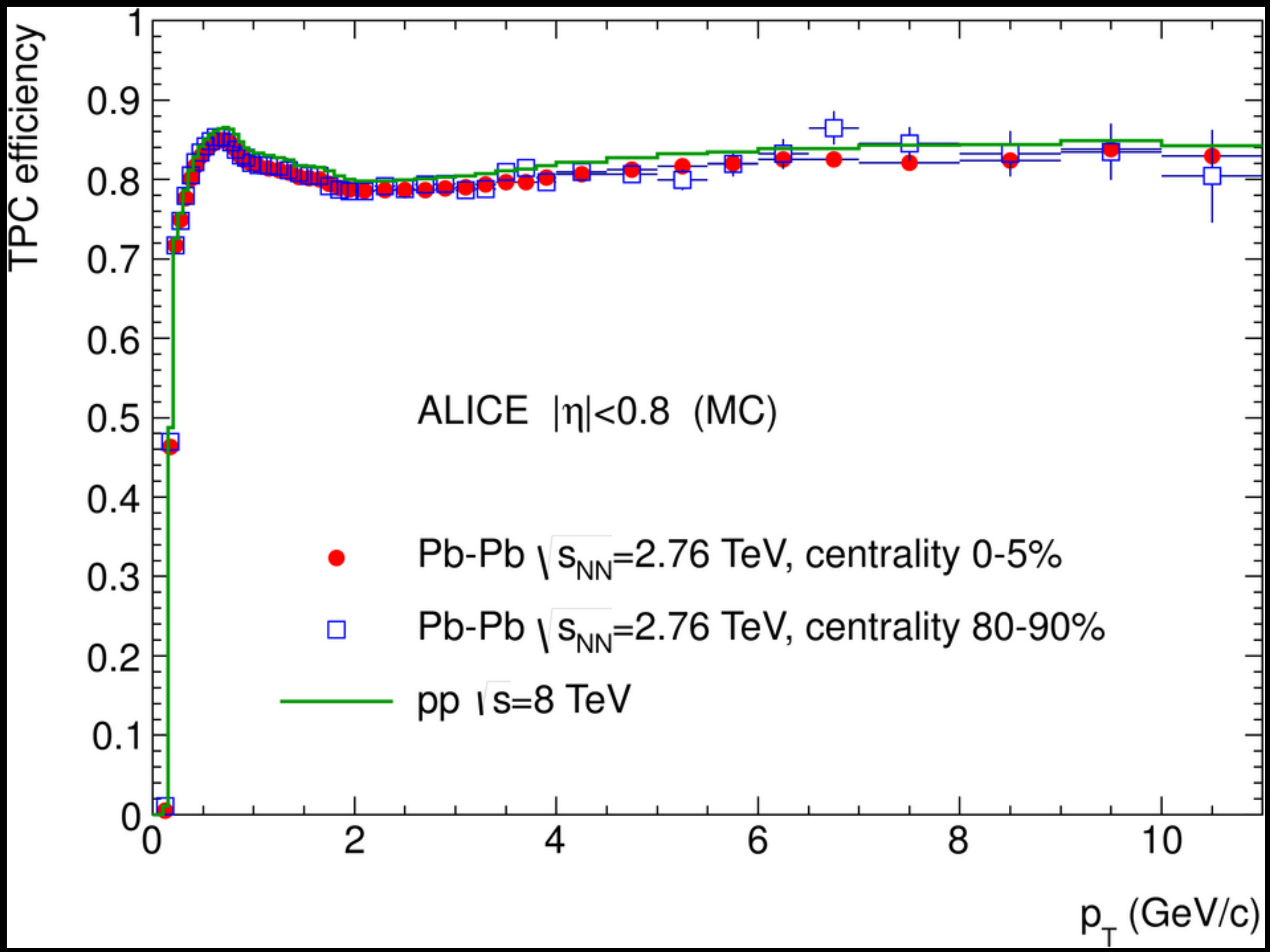
ACORDE
EMCal
HMPID
ZDC
T0A, V0A
PMD
TRD
TOF
PHOS
L3 solenoid
absorber
dipole
TPC
SPD
SDD
SSD
T0C
V0C
MCH
FMD
MTR
ZDC

Detection of charged particles: Gaseous detectors (5)

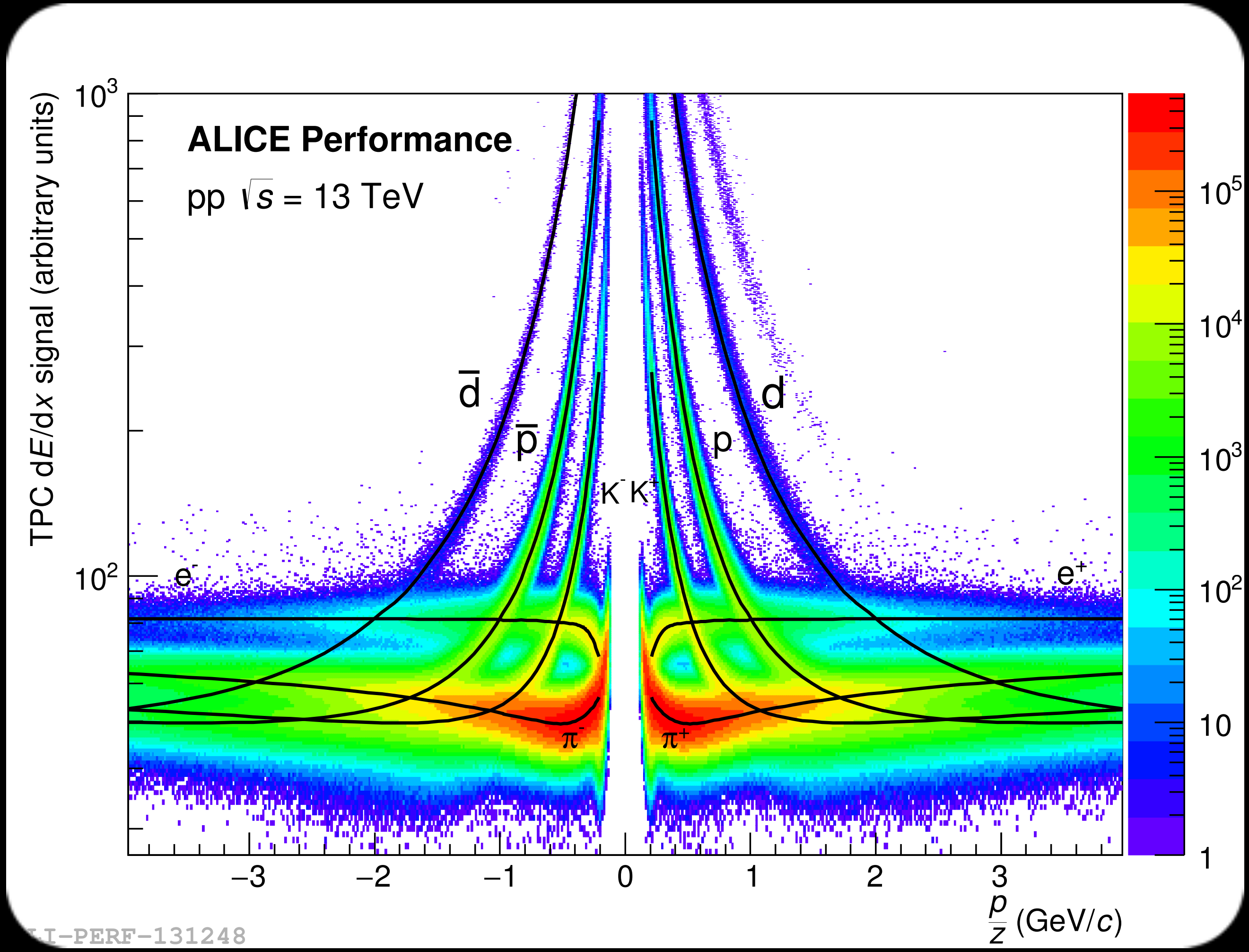
Pseudo-rapidity coverage	$-0.9 < \eta < 0.9$ for full radial track length
	$-1.5 < \eta < 1.5$ for 1/3 radial track length
Azimuthal coverage	360°
Radial position (active volume)	$848 < r < 2466$ mm
Radial size of vessel (outer dimensions)	$606.5 < r < 2780$ mm
Radial size of vessel (drift gas volume)	$788 < r < 2580$ mm
Length (active volume)	2×2500 mm
Segmentation in φ	18 sectors
Segmentation in r	2 chambers per sector
Total number of readout chambers	$2 \times 2 \times 18 = 72$

Detection of charged particles: Gaseous detectors (6)

Main tracking device of ALICE



One of the main identification techniques of ALICE



- ✓ The TPC is able to reconstruct the vast majority of particles being produced in pp and heavy-ion collisions
  - Nch ~ 2000 in central Pb-Pb collisions (to be compared with <10 in pp collisions)

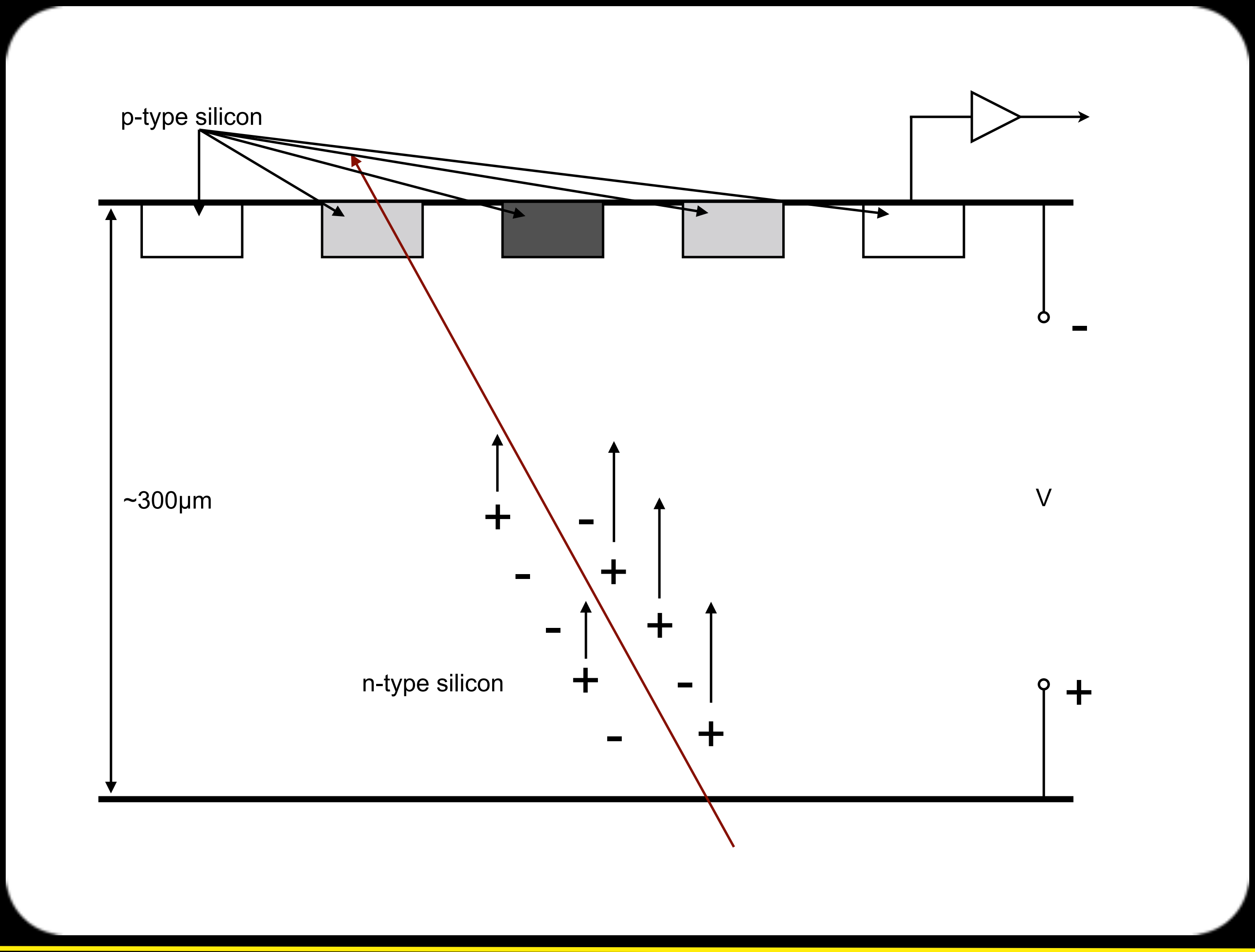
- ✓ Charged particles can be identified with precision
- ✓ One of the main identification techniques utilised in ALICE

Detection of charged particles: semiconductor detectors (1)

- Conductivity: how strongly a given material opposes the flow of electric current
- **Semiconductor: a** material with electrical conductivity value between that of a conductor and an insulator
  - Their resistance decreases as their temperature increases, behaviour opposite to that of a metal.
- Their conducting properties may be altered in useful ways by the deliberate, controlled introduction of impurities
  - this process is called doping
- Where two differently-doped regions exist in the same crystal, a semiconductor junction is created
  - n-type semiconductors have a larger electron concentration than hole concentration. The term *n-type* comes from the negative charge of the electron. In n-type semiconductors, electrons are the majority carriers and holes are the minority carriers
  - p-type semiconductors have a larger hole concentration than electron concentration. The term *p-type* refers to the positive charge of the hole. In p-type semiconductors, holes are the majority carriers and electrons are the minority carriers

Detection of charged particles: semiconductor detectors (2)

- A charged particle traverses a semiconductor (i.e. an appropriately doped silicon wafer)
  - electron-hole pairs are created by the ionisation process
- If a potential difference is applied across the silicon, the holes will drift in the direction of the electric field where they can be collected by the p–n junctions
- the sensors can be shaped into silicon strips, typically separated by ~25μm or into silicon pixels giving a precise two–dimensional space point.



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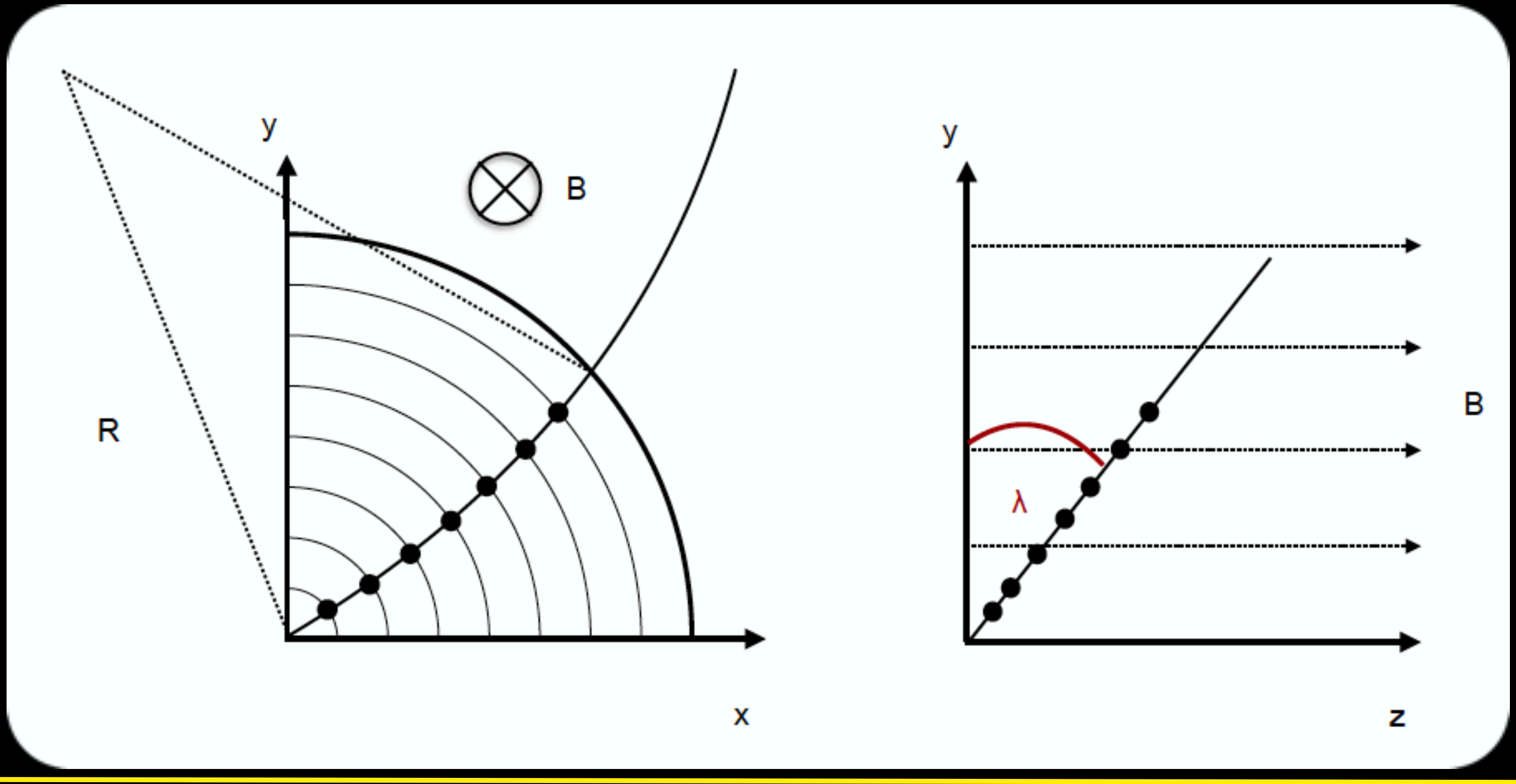
Detection of charged particles: semiconductor detectors (3)

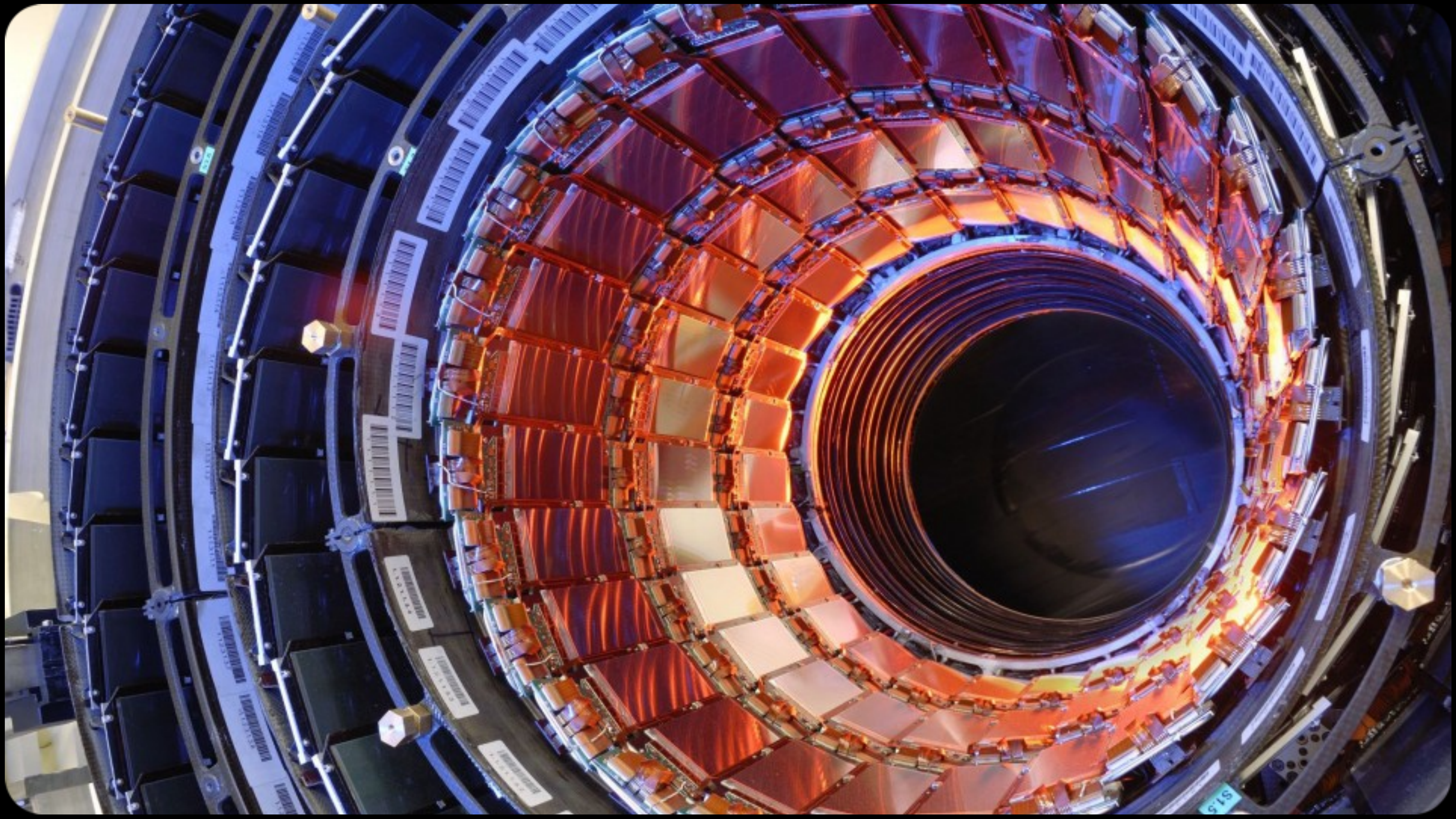
- Silicon tracking detectors typically consist of several layers, cylindrical surfaces of silicon wafers.
- A charged particle will leave a hit on a silicon sensor in each of the cylindrical layers from where the trajectory of the charged particle track can be reconstructed
- The tracking system is usually placed inside a large solenoid producing approximately a uniform magnetic field in the direction of the colliding beams
  - Due to the Lorentz force the trajectory of the particle in the axial magnetic field is a helix with a radius of curvature R and a pitch angle λ

$$p \cos\lambda = 0.3\,BR$$

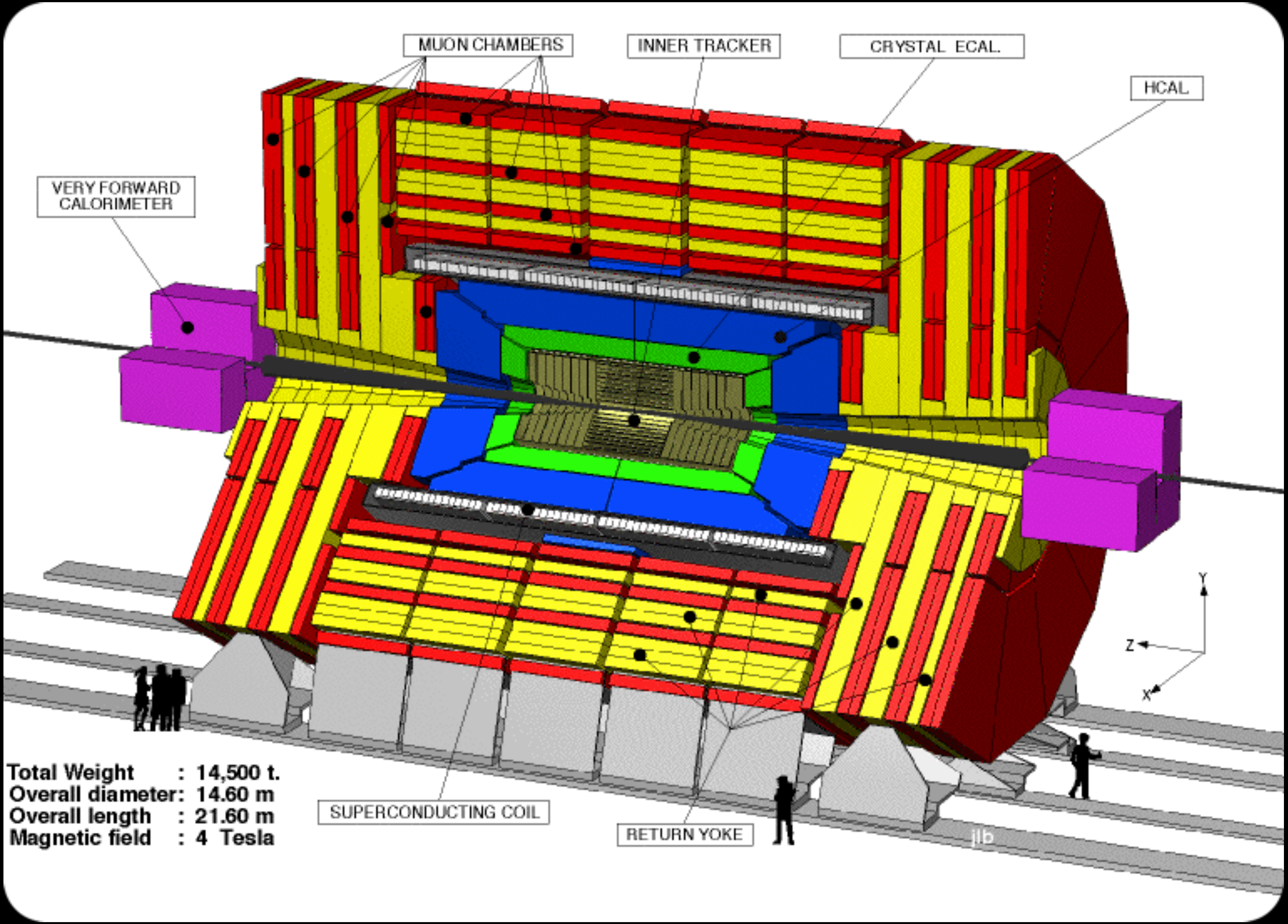


Detection of charged particles: semiconductor detectors (4)

The Si-tracker of the CMS experiment@LHC



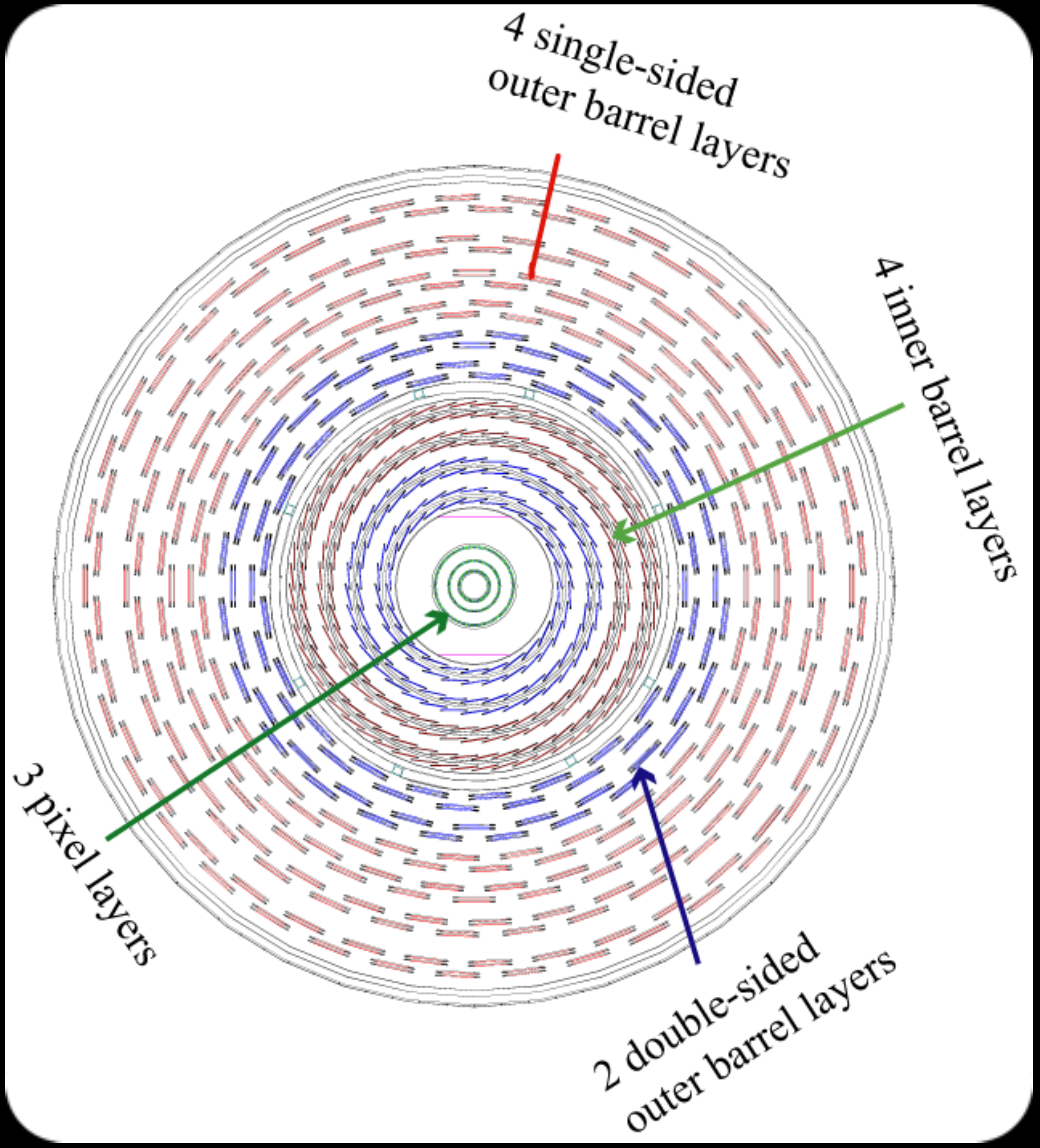
CMS@LHC



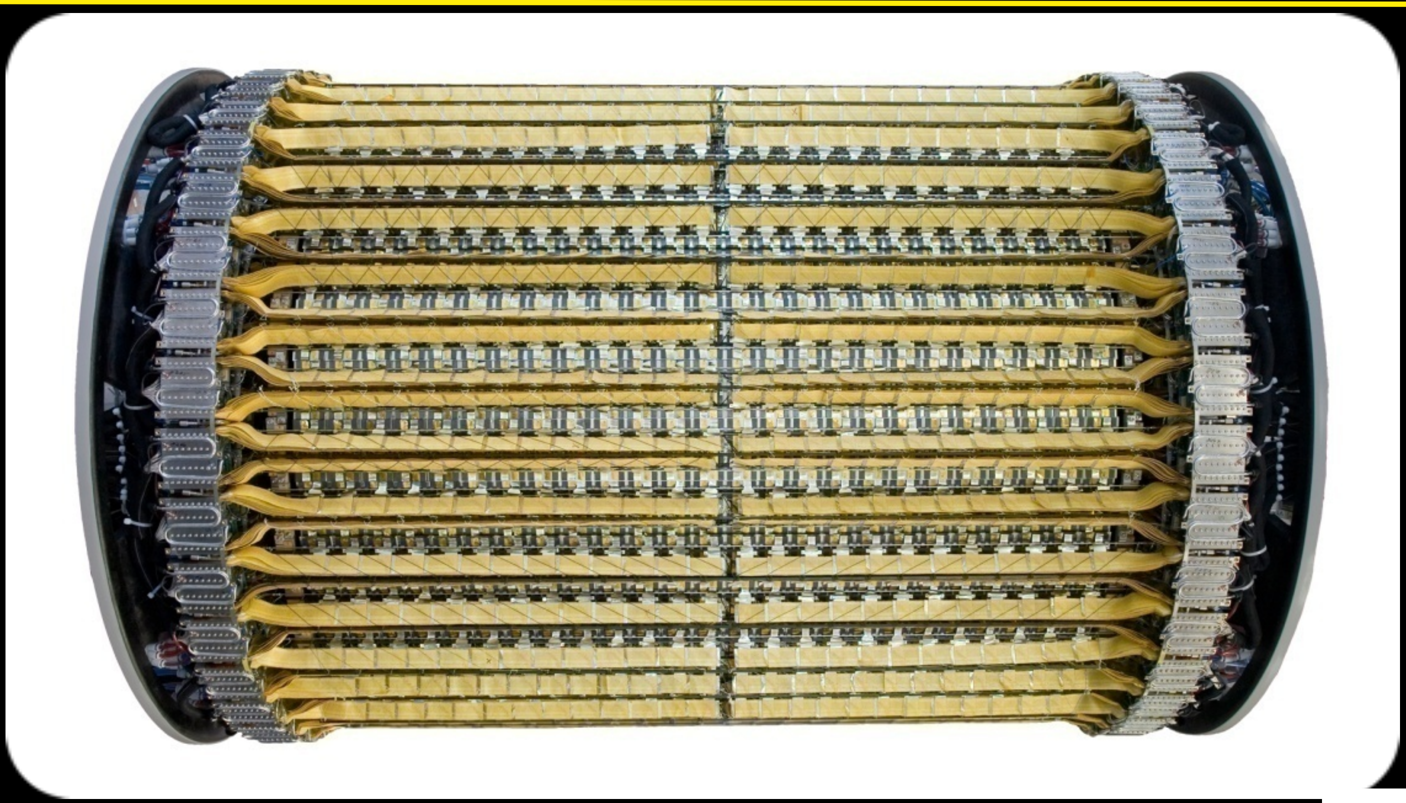
MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL.
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Y
Z
X
jlb
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Detection of charged particles: semiconductor detectors (5)

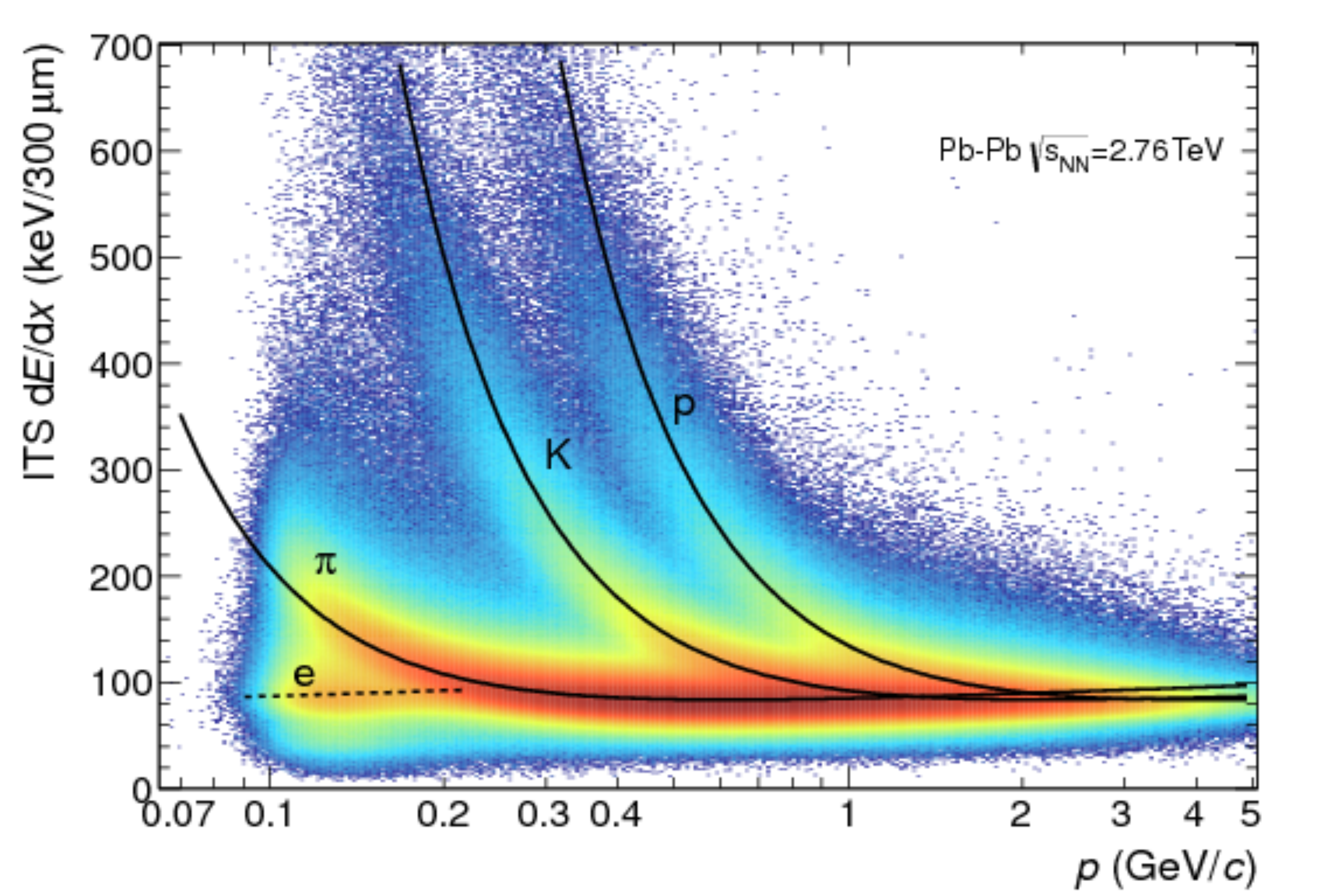
- The pixel detector (the size of a shoebox) contains 65 million pixels, allowing it to track the paths of particles emerging from the collision with extreme accuracy.
  - The closest detector to the beam pipe, with cylindrical layers at 4cm, 7cm and 11cm and disks at either end,
    - the rate of particles received 8cm from the beam line will be around 10 million particles per square centimetre per second.
  - Each layer is split into segments like tiny kitchen tiles, each a little silicon sensor, 100μm by 150μm, about two hairs widths.
- 10 layers of silicon strip detectors, reaching out to a radius of 130 centimetres
  - 4 inner barrel (TIB) layers assembled in shells with two inner endcaps (TID), each composed of three small discs
  - 6 outer barrel (TOB)
  - 2 endcaps (TEC) close off the tracker
    - Each has silicon modules designed differently for its place within the detector.
  - This part of the tracker contains 15,200 highly sensitive modules with a total of 10 million detector strips read by 80,000 microelectronic chips.



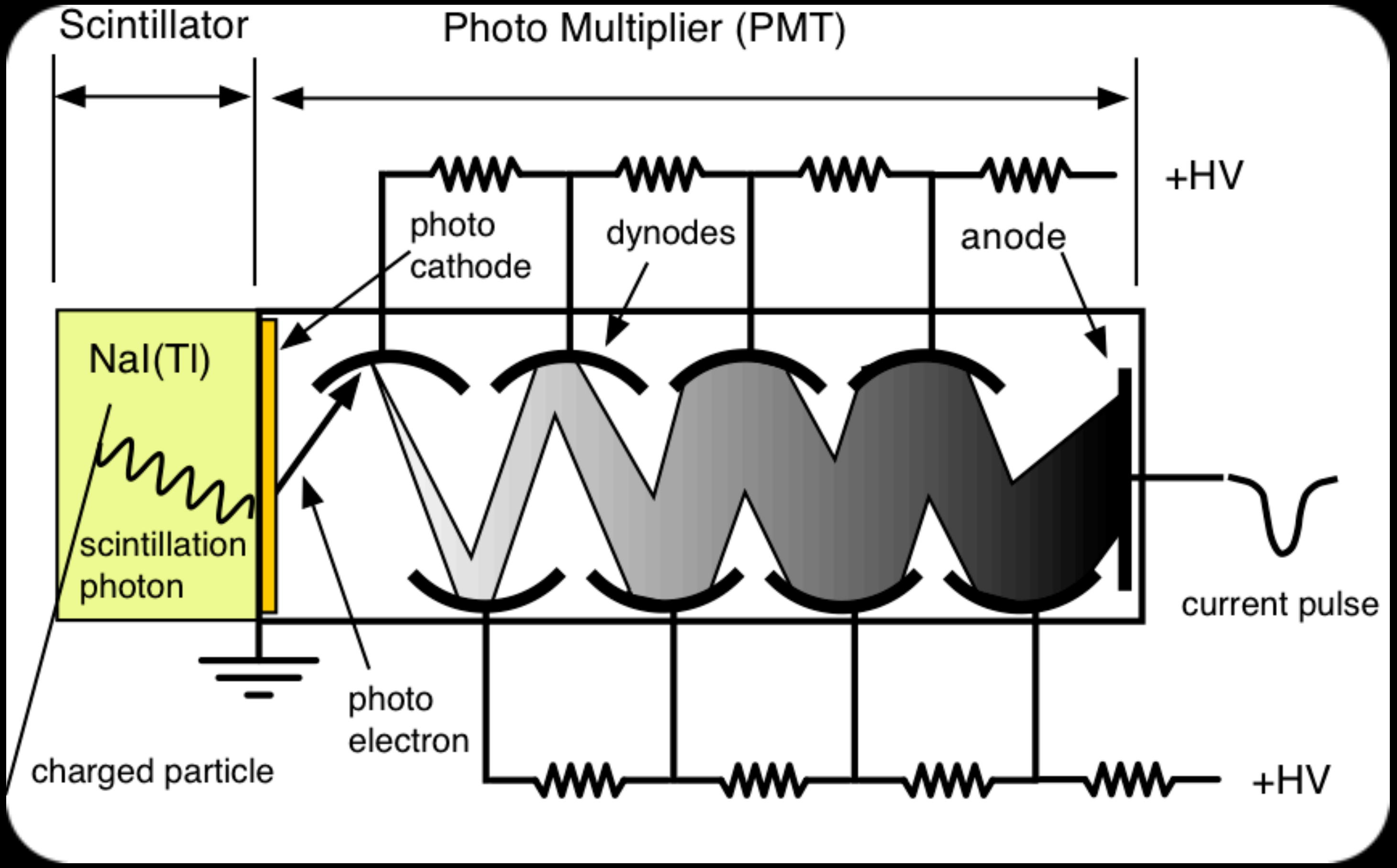
Detection of charged particles: semiconductor detectors (6)



- Charged particles can be identified with silicon detectors
- One of the main identification techniques utilised in CMS (and ALICE; shown here)



Scintillators

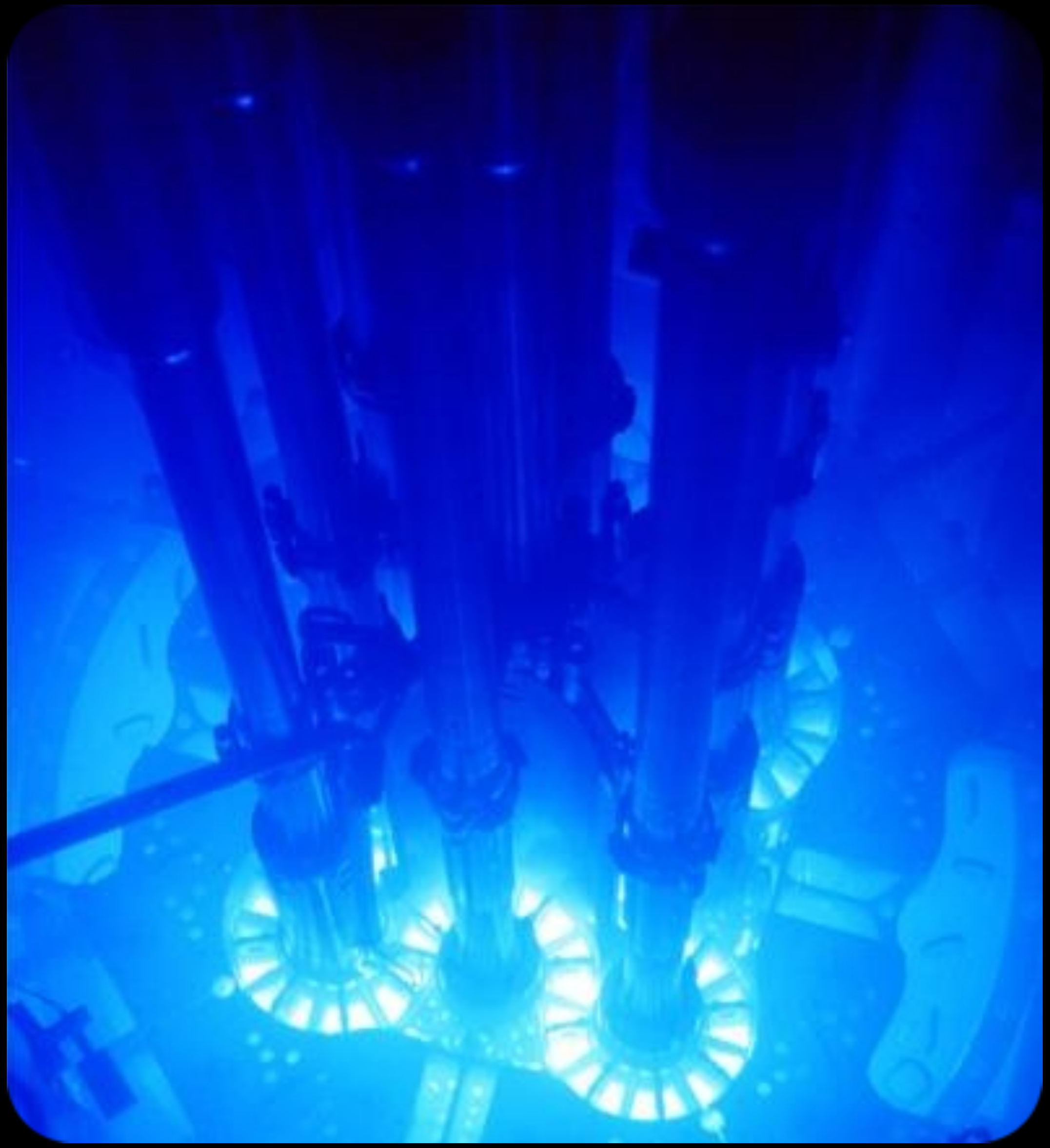


- ✓ Used to signal the passage of charged particles
- ✓ A scintillation detector or scintillation counter couples a scintillator to an electronic light sensor such as a photomultiplier tube (PMT), photodiode, or silicon photomultiplier
  - PMTs absorb the light emitted by the scintillator and re-emit it in the form of electrons via the photoelectric effect
  - The subsequent multiplication of those electrons (sometimes called photo-electrons) results in an electrical pulse → information about the particle that originally struck the scintillator

Cherenkov radiation detectors (1)

- Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium.
  - speed of light in a vacuum is a universal constant but the speed at which light propagates in a material may be significantly less than c
    - e.g. the speed of the propagation of light in water is only 0.75 c
  - As a charged particle travels, it disrupts the local electromagnetic field in its medium. In particular, the medium becomes electrically polarized by the particle's electric field.
    - If the particle travels slowly then the disturbance elastically relaxes back to mechanical equilibrium as the particle passes.
    - When the particle is traveling fast enough, however, the limited response speed of the medium means that a disturbance is left in the wake of the particle, and the energy contained in this disturbance radiates as a coherent shockwave.

Cherenkov radiation emitted inside a nuclear reactor



Cherenkov radiation detectors (2)

- A particle travels in a medium with speed v such that c/n < v < c , where c is the speed of light in vacuum, and n is the refractive index of the medium.
  - e.g. for water, with n=1.33 at T = 20^{o}C then 0.75c < v < c
- The emitted light waves travel at speed $v_{E/M}$ = c/n and at a time t travels a distance of $x_{E/M}$ = ct/n
- At the same time the particle travels a distance x = vt = βct
- The Cherenkov angle is then given by $\cos\theta = \frac{1}{n\beta}$

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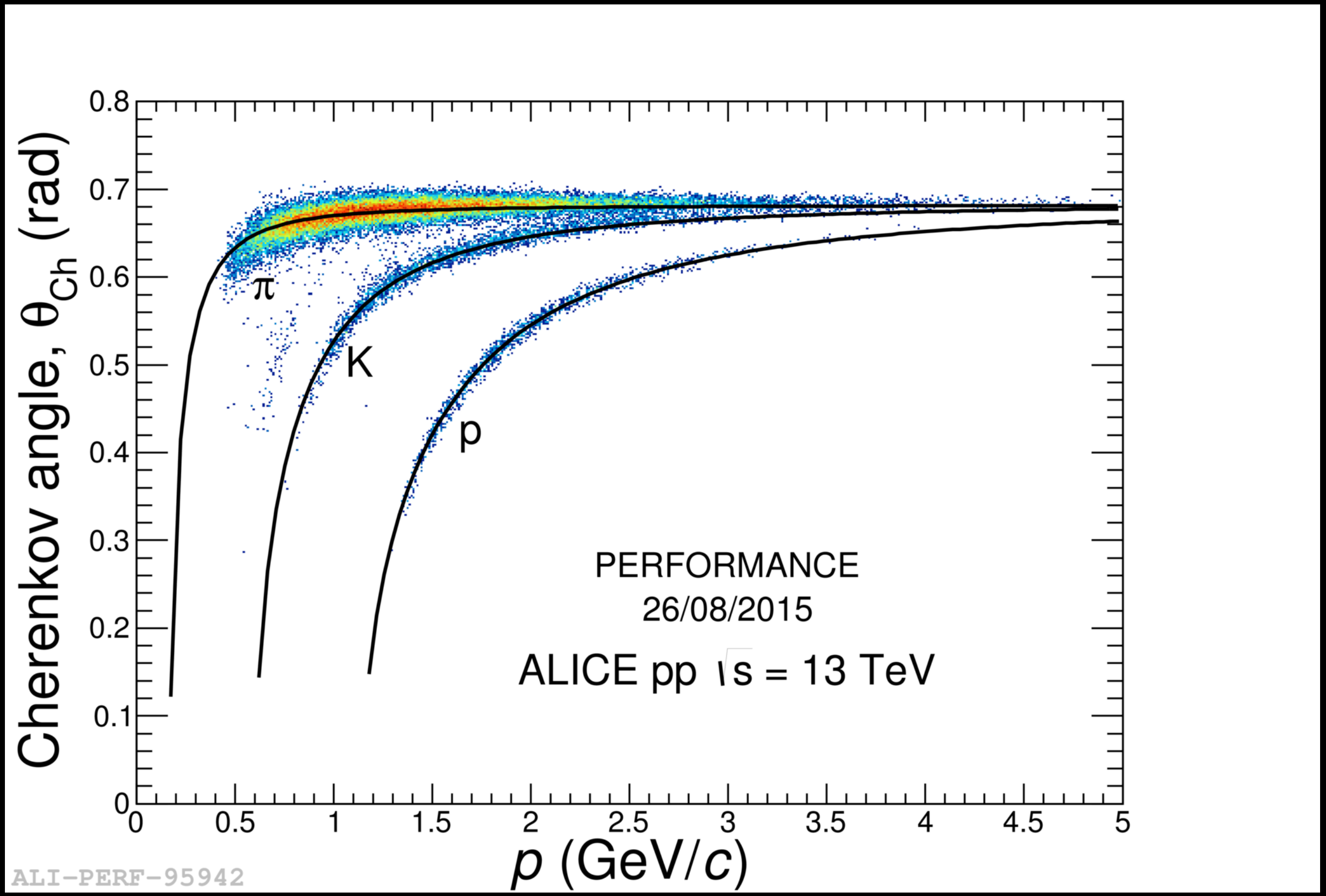
Cherenkov radiation detectors (3)



- The simplest type of particle identification device based on a Cherenkov radiation technique is the threshold counter
  - gives an answer as to whether the velocity of a charged particle is lower or higher than a certain value by looking at whether this particle does or does not emit Cherenkov light in a certain medium
  - this threshold behaviour can be utilised to identify particles of a given momentum p
    - for a relativistic particle $\beta = Pc/E = P/(P^2 + m^2c^2)^{1/2}$
      - particles emitting Cherenkov radiation must have a mass $mc < \sqrt{n^2-1}\, P$

Transition radiation detectors

- Transition radiation (TR) is a form of electromagnetic radiation emitted when a charged particle passes through inhomogeneous media, such as a boundary between two different media
  - in contrast to Cherenkov radiation, which occurs when a charged particle passes through a homogeneous dielectric medium at a speed greater than the phase velocity of electromagnetic waves in that medium
- Optical transition radiation is produced by relativistic charged particles when they cross the interface of two media of different dielectric constants
  - The emitted radiation is the homogeneous difference between the two inhomogeneous solutions of Maxwell's equations of the electric and magnetic fields of the moving particle in each medium separately
    - since the electric field of the particle is different in each medium, the particle has to "shake off" the difference when it crosses the boundary
- In the approximation of relativistic motion ($\gamma \gg 1$), small angles ($\theta \ll 1$) and high frequency ($\omega \gg \omega_p$), where ω_p is the plasma frequency, z is the atomic charge, e is the charge of an electron, the total emitted energy is given by

$$I = \frac{z^2 e^2 \gamma \omega_P}{3c}$$

- Suitable for particle discrimination, particularly of electrons and hadrons in the momentum range between 1 GeV/c and 100 GeV/c

Interaction and detection of electrons and photons

Interaction of electrons with matter (1)

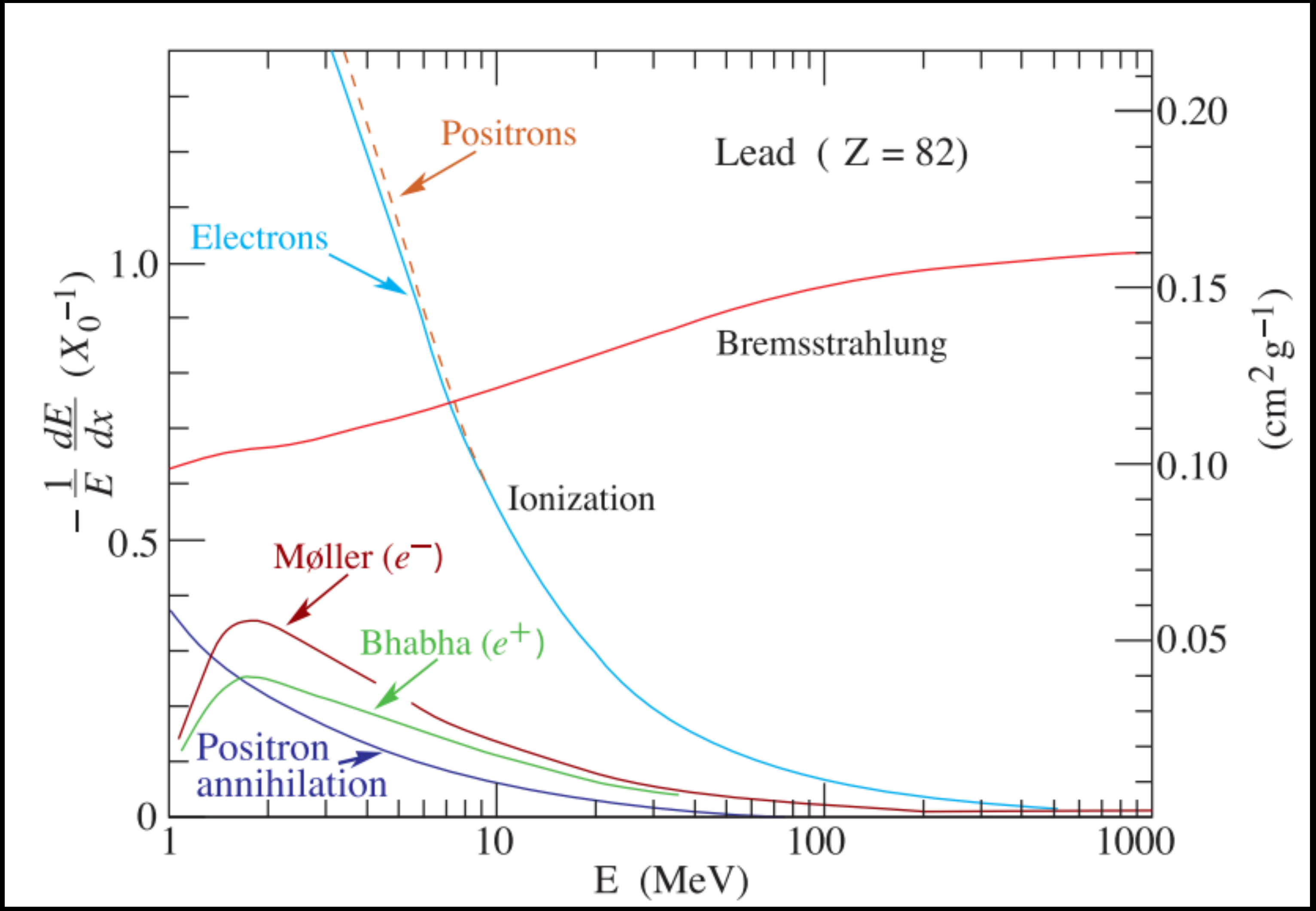
- At low energies the energy loss of electrons is dominated by ionisation
- For energies above a critical energy E_{cr} the main energy loss mechanism is bremsstrahlung
  - the electron radiates a photon in the presence of the electrostatic field of a nucleus
  - The critical energy is related to the charge Z of the nucleus and is given by

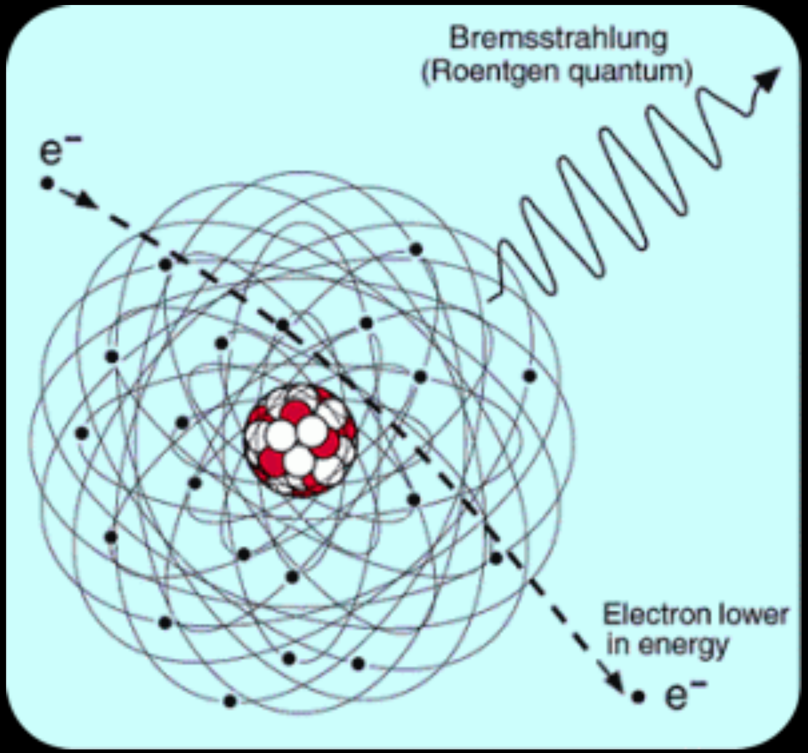
$$E_{cr} \approx \frac{800}{Z} MeV$$

- The electrons of interest in the majority of the modern particle physics experiments have an energy at the multi-GeV scale
  - significantly larger than the critical energy
  - interact with matter primarily through bremsstrahlung
- The bremsstrahlung effect can occur for all charged particles but the rate is inversely proportional to the square of the mass of the particle
  - for muons the rate of energy loss through bremsstrahlung is suppressed compared to electrons by a factor of $(m_e/m_\mu)^2$
  - Muons mainly lose energy by ionisation, while energetic electrons the dominant mechanism is bremsstrahlung

Interaction of electrons with matter (2)

- Bremsstrahlung is electromagnetic radiation produced by the acceleration or deceleration of a charged particle when
  - deflected by magnetic fields (an electron by magnetic field of particle accelerator)
  - In the presence of another charged particle (an electron by an atomic nucleus)

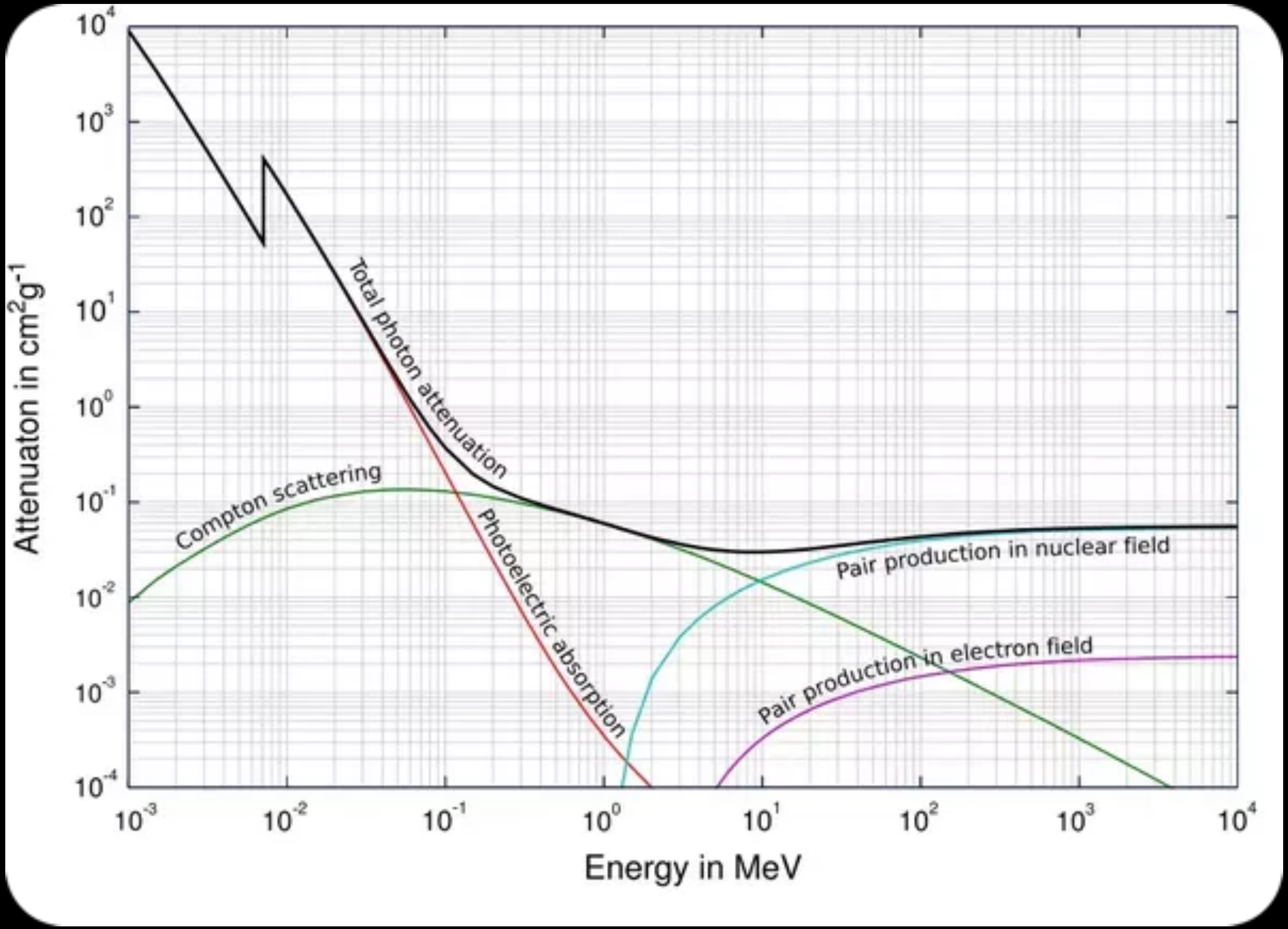




Fractional energy loss per radiation length in lead as a function of electron or positron energy

Interaction of photons with matter (1)

- Photons, at low energies, interact with matter primarily via the photoelectric effect.
  - a photon is absorbed by an atomic electron that is ejected from the atom
- At higher energies, $E_\gamma \sim 1$ MeV, the Compton scattering process ($\gamma + e^- \rightarrow \gamma + e^-$) becomes significant
- For even higher energies, for $E_\gamma > 10$MeV, the interactions of photons are dominated by electron-positron pair production in the presence of the field of a nucleus



Interaction of photons with matter (2)

- ✓ The electromagnetic interactions of high energy electrons and photons in matter is characterised by the **radiation length X_0**
- ✓ The radiation length is the average distance over which the energy of an electron is reduced by bremsstrahlung by a factor of 1/e
- ✓ It is approximately 7/9 of the mean free path of the e^+-e^- pair production for a high-energy photon
- ✓ The radiation length is related to the atomic number Z of the material and can be approximated by the expression

$$X_0 = \frac{1}{4\alpha n Z^2 r_e^2 \ln(287/Z^{1/2})}$$

  - where n is the number density of nuclei and r_e is the classical radius of the electron
- ✓ For high-Z materials the radiation length is relatively short
  - As an example $X_0(Fe) = 1.76$cm and $X_0(Pb) = 0.56$cm

Electromagnetic showers (1)

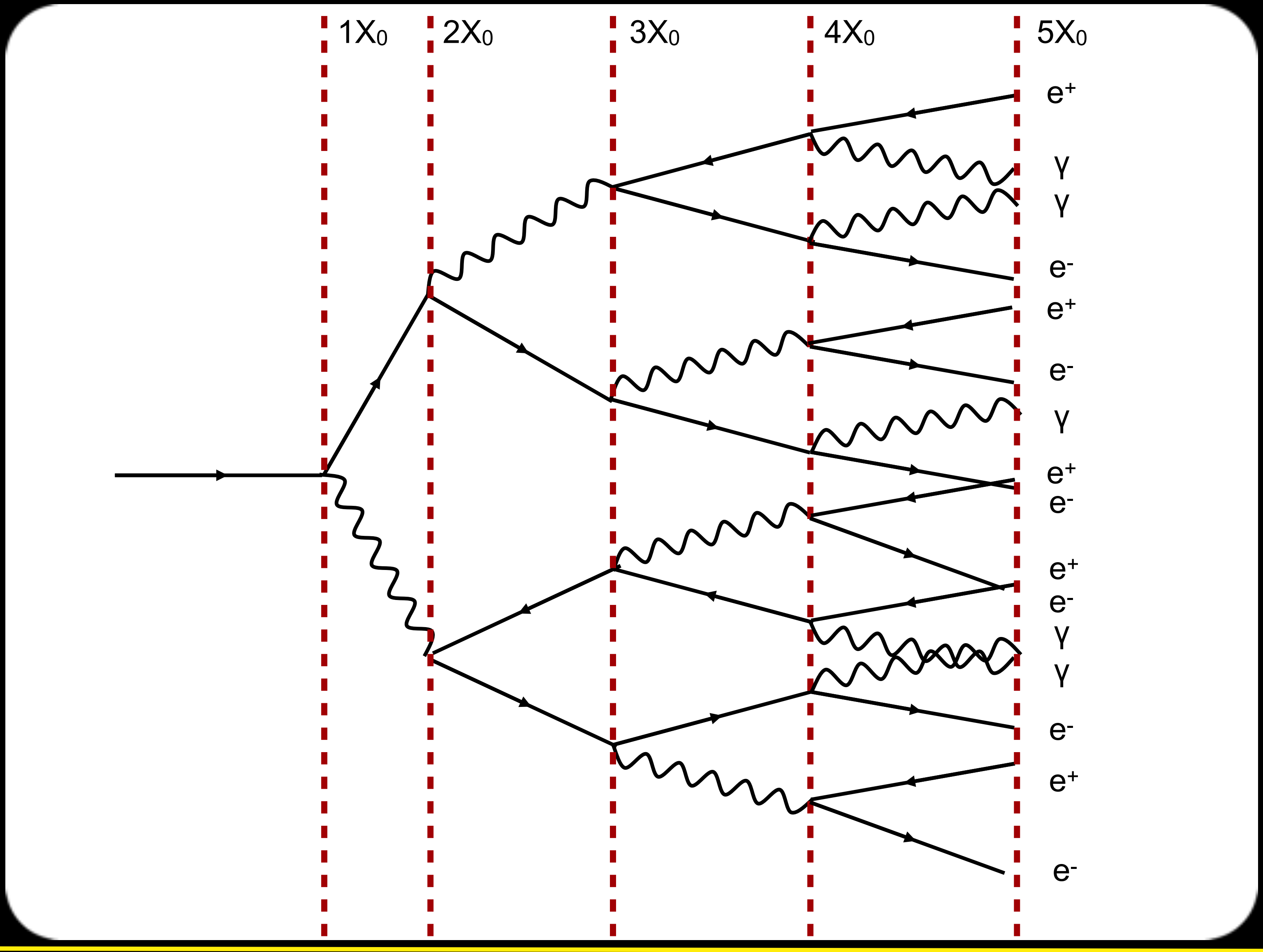
- When a high-energy electron interacts with matter in a medium it radiates a bremsstrahlung photon
  - which in turns produces an electron-positron pair
- The process of bremsstrahlung and pair production continues to produce a cascade of photons, electrons and positrons
- This whole process is referred to as electromagnetic shower
- Similarly a high-energy photon will create an electron-positron pair
  - This pair will in turns produce an electromagnetic shower

Electromagnetic showers (2)

- The number of particles in an electromagnetic shower approximately doubles after every radiation length of material traversed

- In an electromagnetic shower produced by an electron or photon of energy E, the average energy of particles after x radiation lengths is given by

$$\langle E \rangle = \frac{E}{2^x}$$



Electromagnetic showers (3)

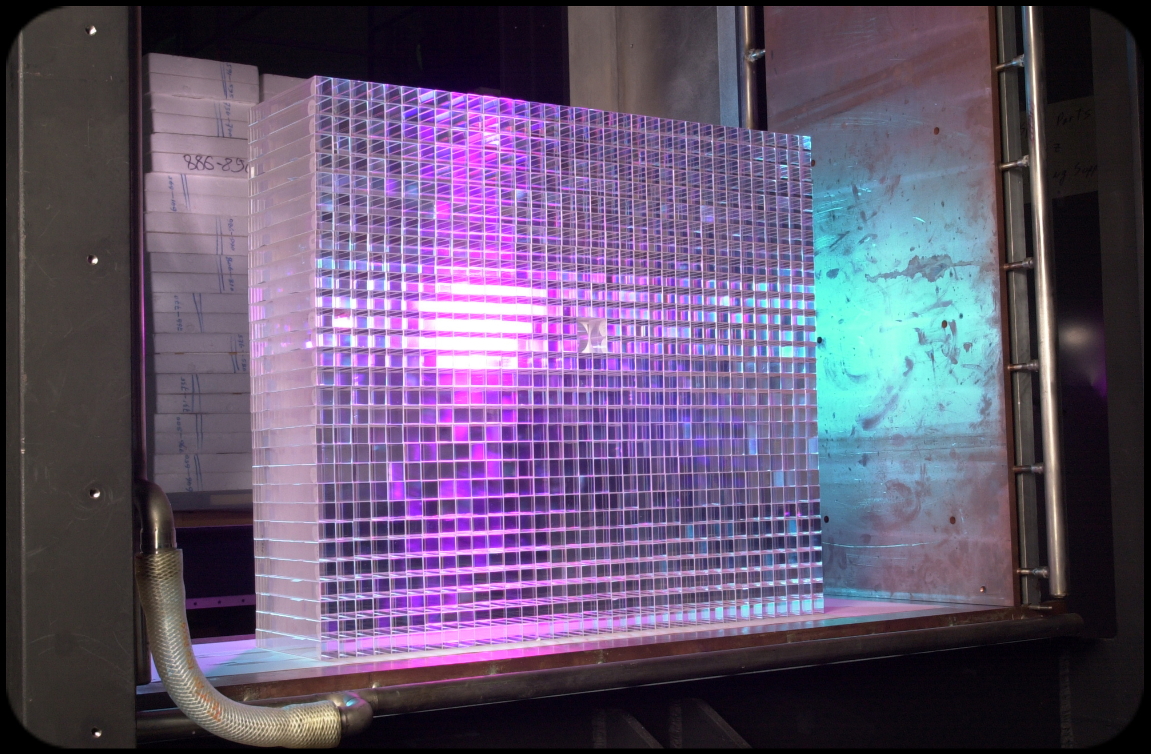
- The shower continues to develop until the average energy of the particles falls below the critical energy (E_{cr})
  - Beyond this point the electrons and positrons in the cascade lose energy primarily through ionisation
- The electromagnetic shower has thus the maximum number of particles after X_{max} radiation lengths given by the condition $\langle E \rangle = E_{cr}$
  - This point is reached after

$$X_{max} = \frac{\ln\left(\frac{E}{E_{cr}}\right)}{\ln 2}$$

- In a high-Z material such as lead with $E_{cr} \sim 10$MeV, a 100GeV electromagnetic shower reaches its maximum at ~13 X_0
  - This corresponds to about 10cm of lead
  - Consequently electromagnetic showers deposit most of their energy in a relatively small region of space.

Electromagnetic calorimeters (1)

- In high-energy particle physics experiments the energies of electrons and photons are measured using electromagnetic calorimeters constructed from high-Z material
- A popular choice is the usage of lead tungstate ($PbWO_4$) crystals which is an inorganic scintillator
  - These crystals are both optically transparent and have a short radiation length of X_0 = 0.83cm, allowing the electromagnetic shower to be contained in a compact region
  - The electrons in the electromagnetic shower produce scintillation light that can be collected and amplified by efficient photon detectors
    - The amount of scintillation light produced is proportional to the total energy of the original electron or photon



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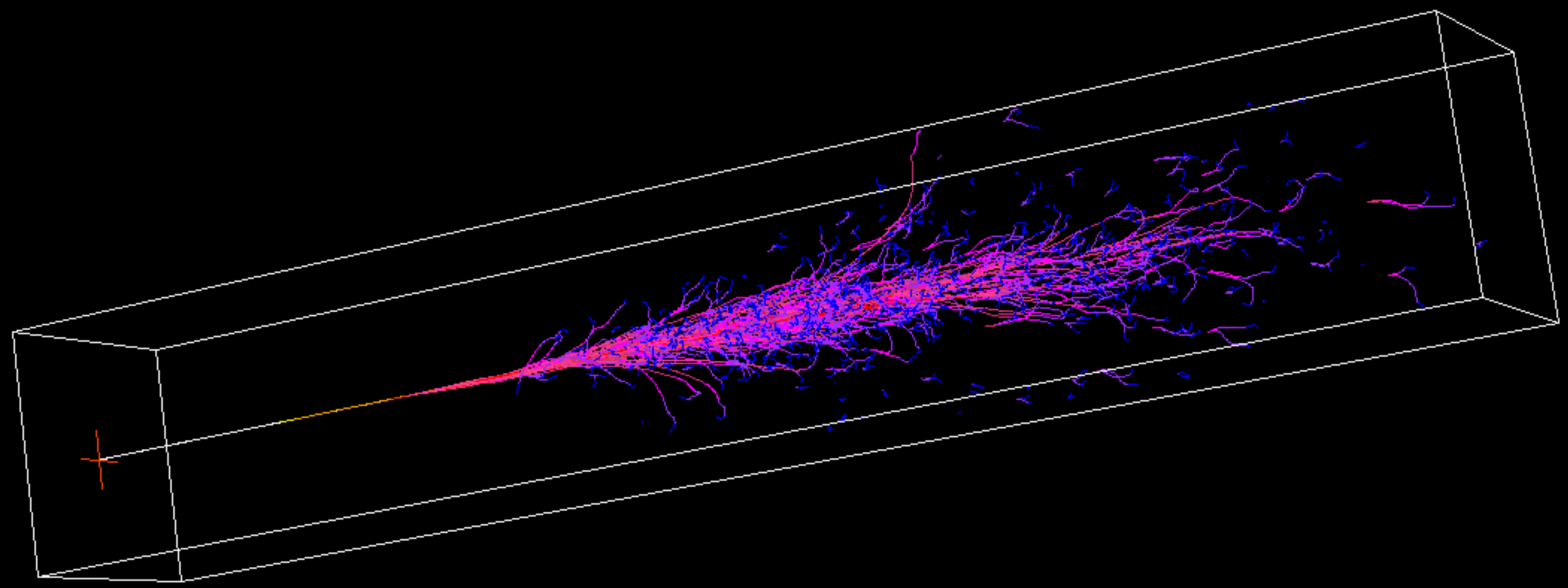
Electromagnetic calorimeters (2)

- ✓ Alternatively, electromagnetic calorimeters can be constructed by alternating layers of high-Z material, such as lead, with an active layer in which the ionisation from the electrons in the electromagnetic shower can be measured



- ✓ For the electromagnetic calorimeters in large, modern particle physics detectors, the energy resolution for electrons and photons is typically in the range

$$\frac{\sigma_E}{E} \approx \frac{3\text{–}10\%}{\sqrt{E}}$$

Interaction and detection of hadrons

Hadronic showers (1)

- Charged hadrons lose energy continuously through ionisation when they interact with matter

- In addition, both charged and neutral hadrons can undergo strong interactions with the nuclei of the medium

- Particle produced in this primary hadronic interaction will subsequently interact further downstream in the medium, giving rise to a cascade of particles of hadronic, this time, nature

- The development of hadronic showers is characterised by the **nuclear interaction length λ_f**
  - defined as the mean distance between hadronic interactions of relativistic hadrons

- The nuclear interaction length is significantly larger than the radiation length
  - As an example, the interaction length for Fe is $\lambda_f(Fe) \sim 17cm$, compared to its radiation length of $X_0(Fe) = 1.76cm$

Hadronic showers (2)

- Unlike electromagnetic showers which develop in a uniform manner, hadronic showers are more variable because of the many different final stets that can be produced in high-energy hadronic interactions

- In addition, any π^0 produced in the hadronic shower decays almost instantaneously through the channel $\pi^0 \rightarrow \gamma + \gamma$
  - electromagnetic component of the shower
  - The fraction of the energy in this electromagnetic component depends on the number of π^0 produced and varies from shower to shower

- Not all of the energy in a hadronic shower is detectable
  - On average, around 30% of the incident energy is effectively lost in the form of nuclear excitation and break-up

Hadronic calorimeters

- In particle detector systems the energies of such hadronic showers are measured in a hadron calorimeter
- Because of the relatively large distance between nuclear interactions, hadronic showers will occupy a significant volume in any detector
  - For example, in a typical hadron calorimeter, the shower of a 100~GeV hadron has longitudinal and lateral extents of the order of 2m and 0.5m, respectively.
- A commonly used technique is to use a sandwich structure of thick layers of high-density absorber material, where the shower develops, and thin layers of active material where the energy deposition from the charged particle in the shower are sampled
- Fluctuations in the electromagnetic fraction of the shower and the amount of energy lost in nuclear break-up limits the precision to which the energy can be measured
  - A typical value for the energy resolution of a hadronic calorimeter is given by

$$\frac{\sigma_E}{E} \geq \frac{50\%}{\sqrt{E}}$$

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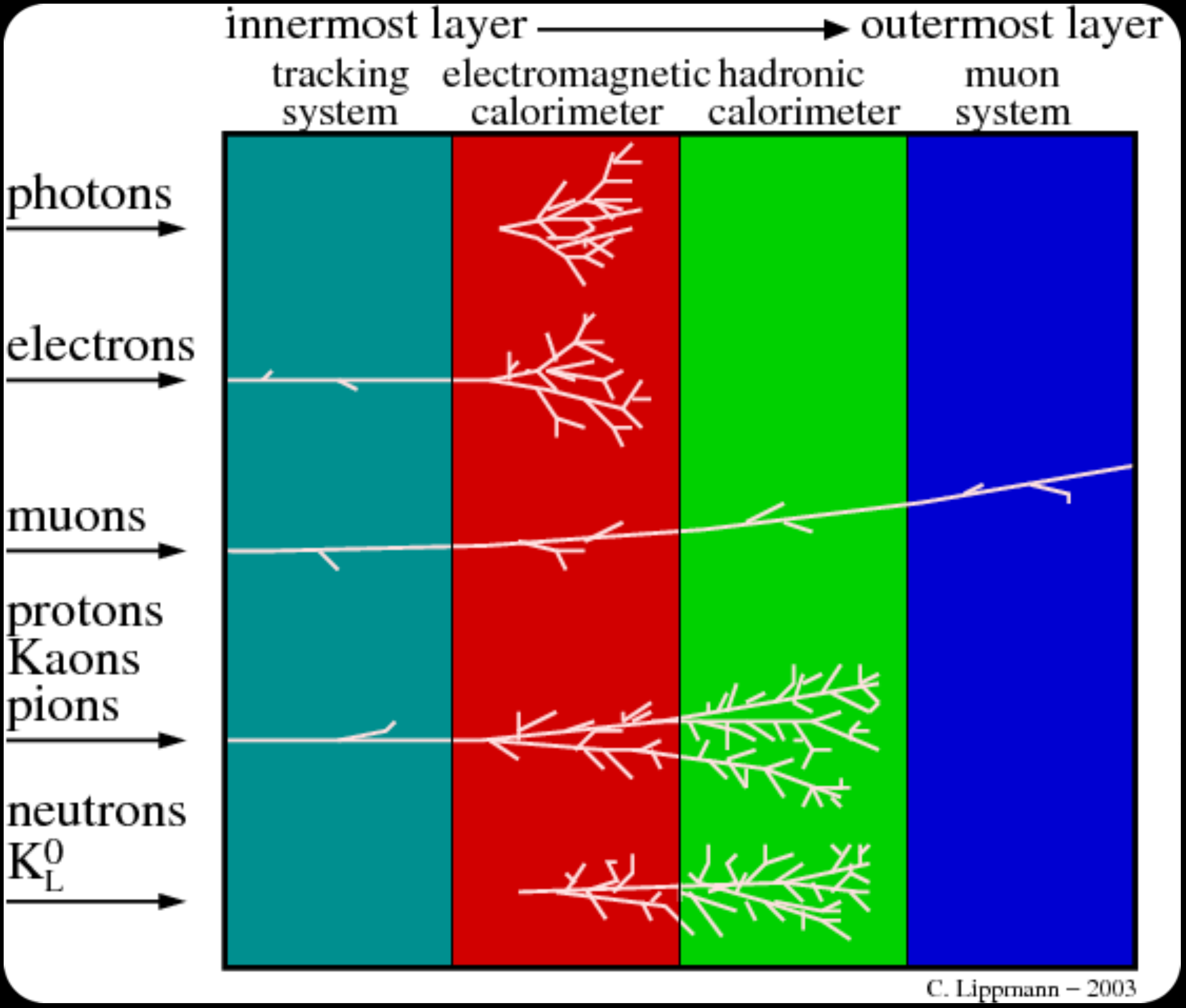
Setup of modern particle physics experiments

Basic considerations



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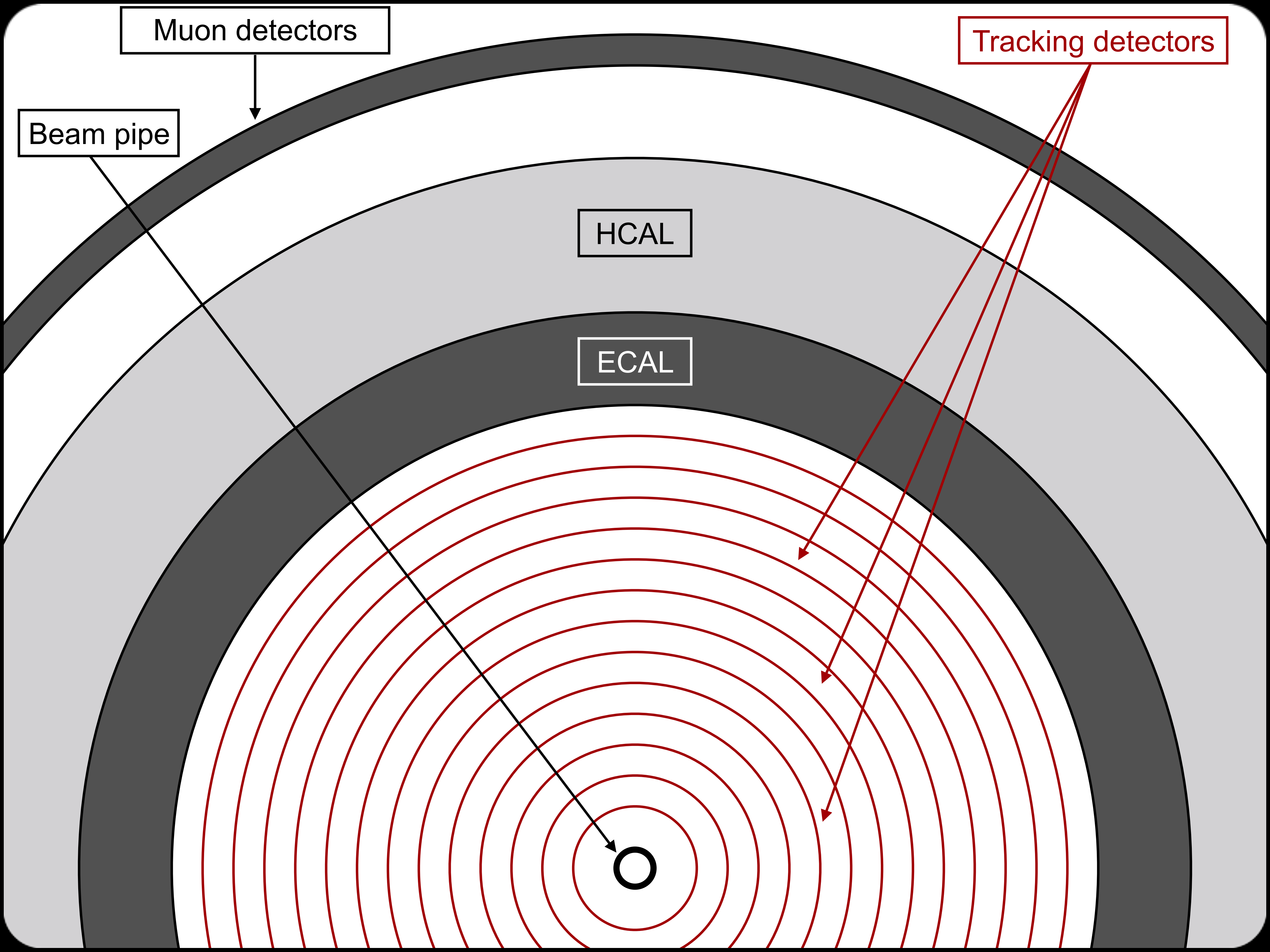
Basic setup (1)



Basic setup (2)

- To measure the momentum of particles, as discussed before, a suitable (usually solenoid) magnetic fields is applied inside this barrel region
- **Electrons** are identified as charged-particle tracks that leave hits in the **tracking detectors** and subsequently initiate an electromagnetic shower in the **electromagnetic calorimeter**
- **Neutral particles** are either reconstructed in the **tracking detectors** (e.g. decays) or their energy is measured in **calorimeters**
  - **Photons** are identified in the electromagnetic calorimeter as sources of isolated showers
  - **Neutral hadrons** will interact with the material in the hadronic calorimeter and initiate an isolated hadronic shower
- **Charged hadrons** will be reconstructed from their hits in the **tracking detectors**, followed by the combination of a **small energy deposition** via ionisation energy loss in the **electromagnetic calorimeter** and a **large energy deposition** in the **hadronic calorimeter**
- **Muon tracks** are detected by **special detectors** outside the calorimeters are sensitive to their passage, in combination with hits in the **tracking detectors** and very **small energy deposition** in both the **electromagnetic and the hadronic calorimeters**

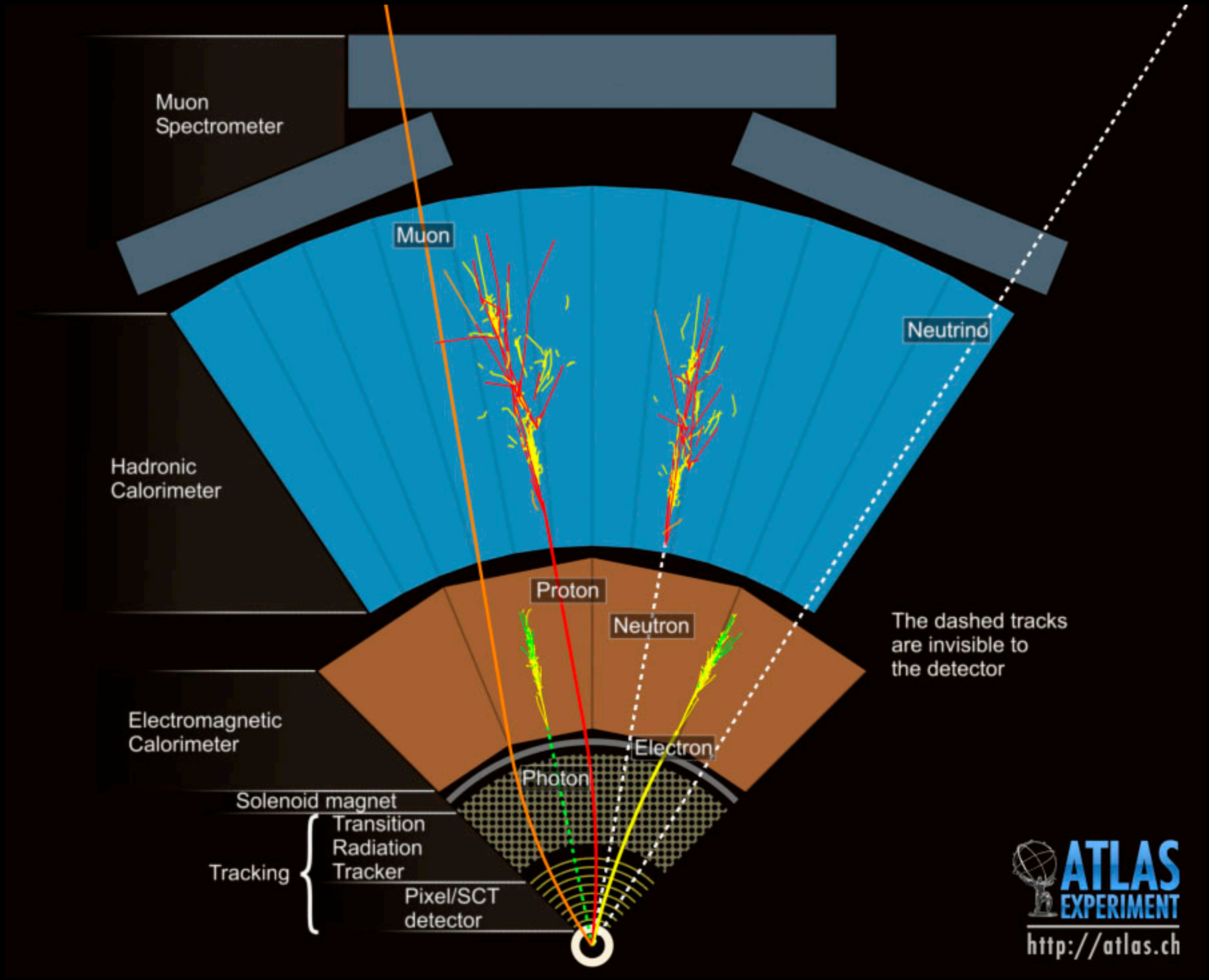
Basic setup (3)

- One of the last pieces of the puzzle is the detection of **neutrinos**
- Neutrinos barely interact with matter
- However they are carriers of important information and thus need to be accounted for
- Their presence in modern particle physics experiments, whose purpose is not solely the detection of neutrinos, is through the presence of missing momentum, defined as

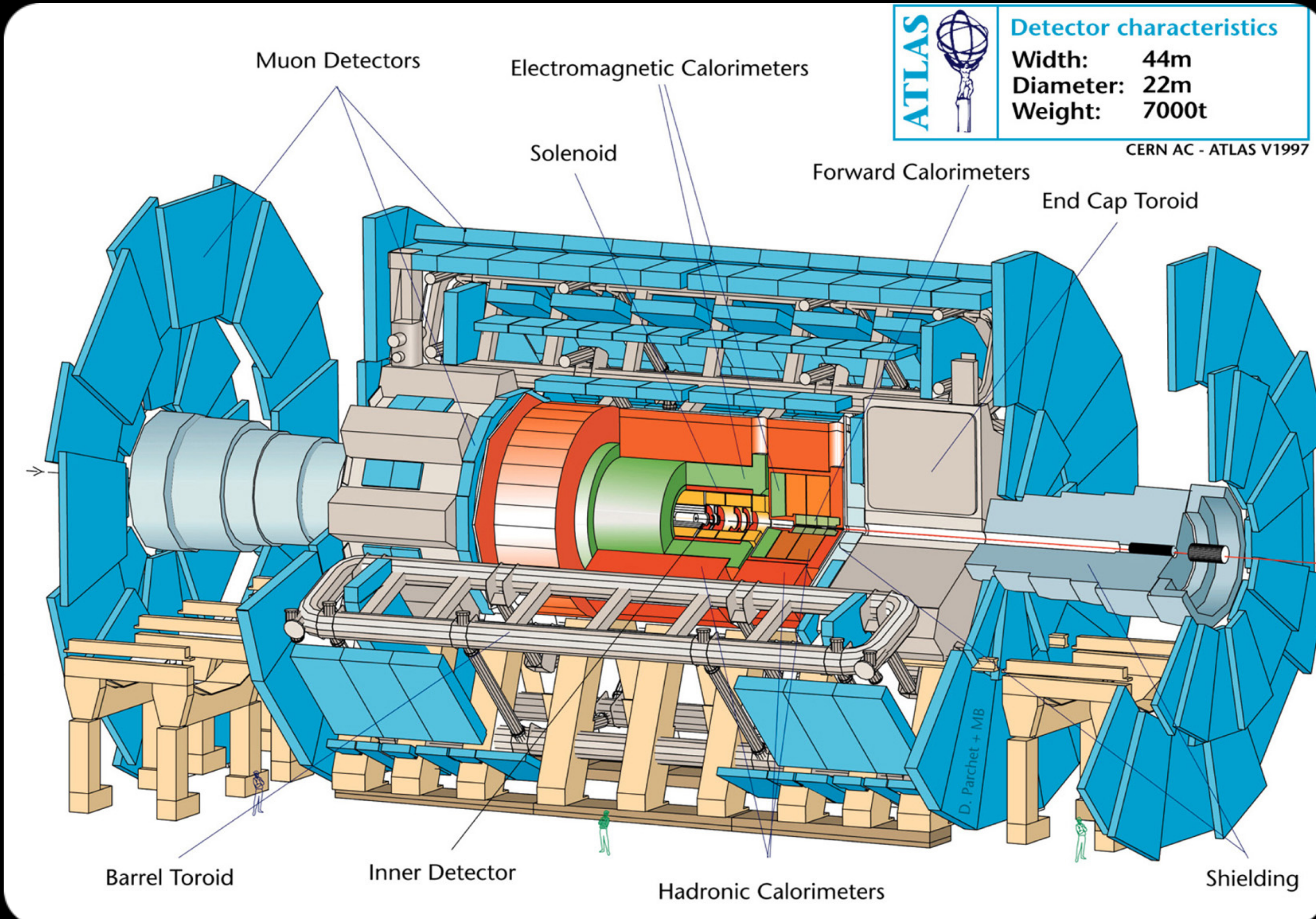
$$\vec{P}_{missing} = -\sum_{i=1}^{N} \vec{P}_i$$

  - where the sum extends over all measured momenta of all observed particles in all directions of an event
  - If all particles produced in the collision are detected, this sum should be zero provided that the collisions take place in the centre-of-mass frame
  - Any significant deviation from zero indicates the presence of energetic neutrinos in the event

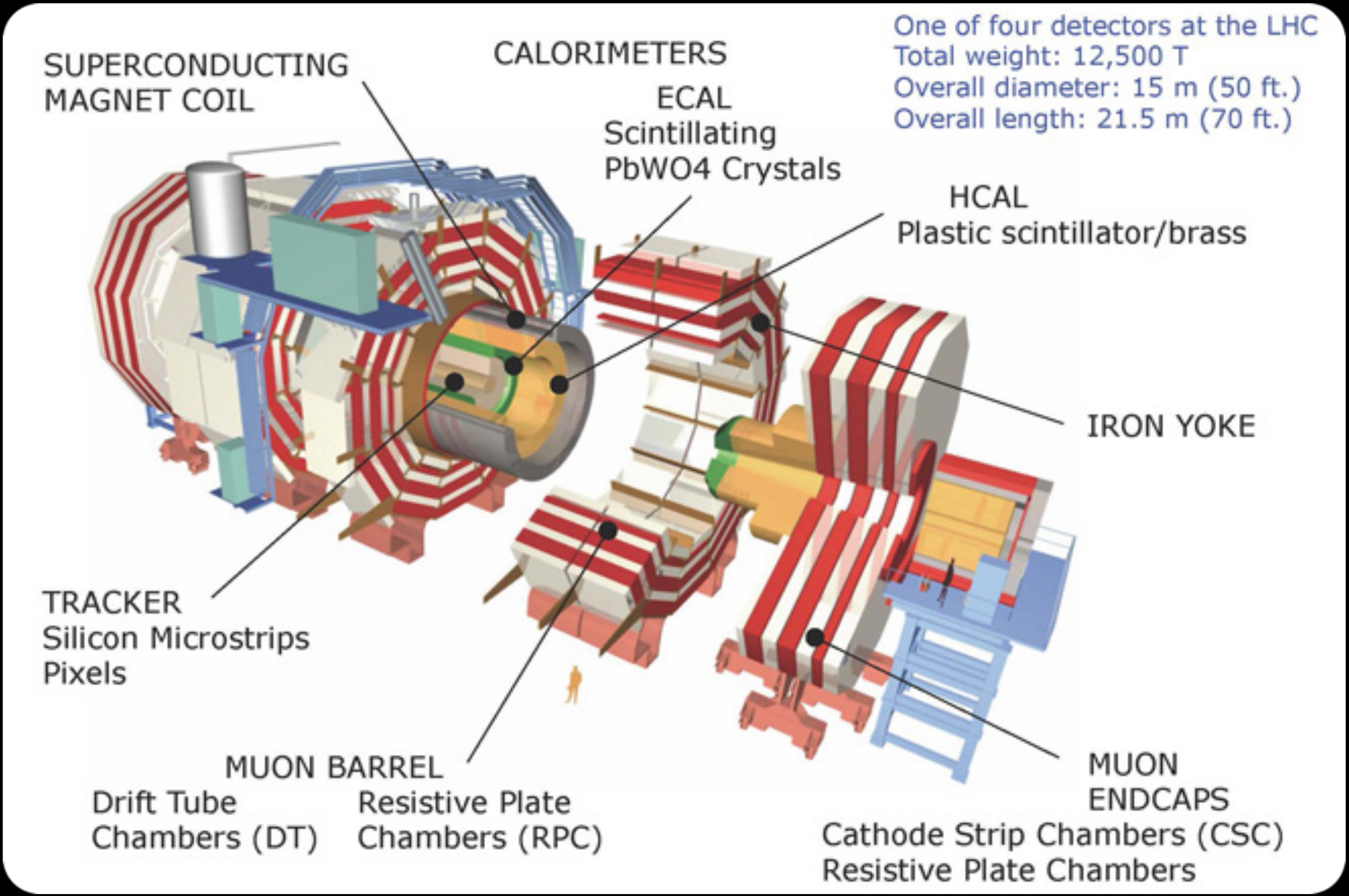
An example…


Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

The ATLAS detector @ LHC



The CMS detector @ LHC



Particle accelerators

Categories of particle accelerators

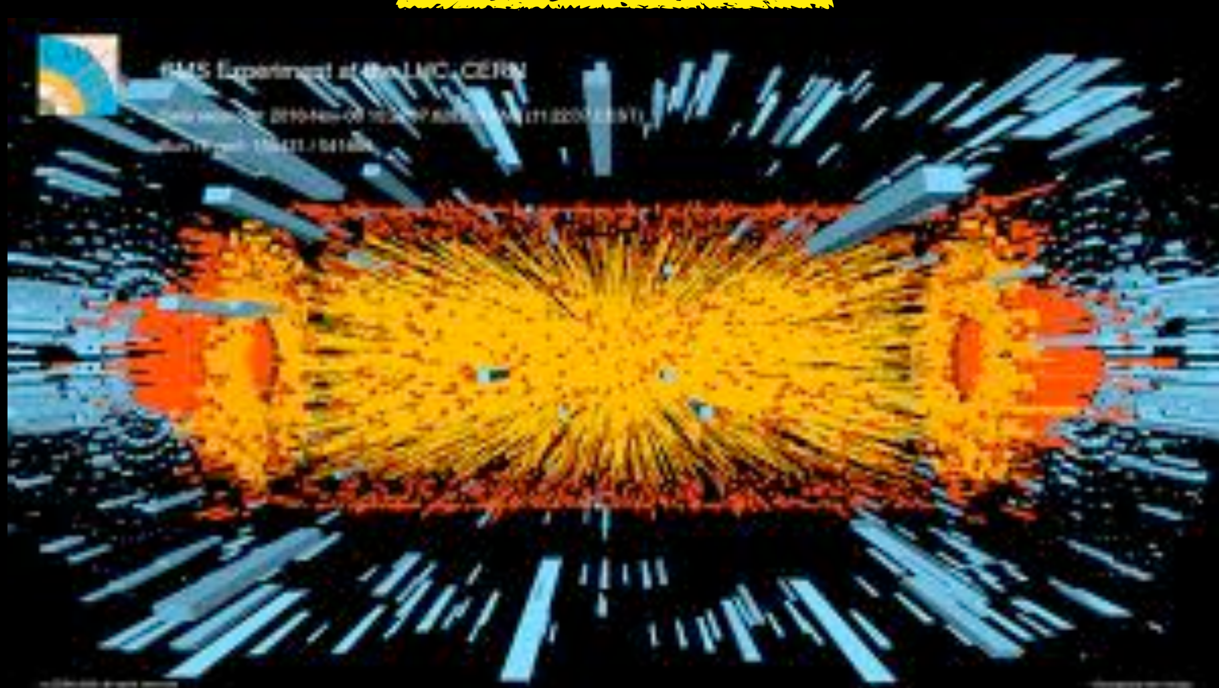
- Major breakthroughs in particle physics have come from experiments at high-energy particle accelerators.

- Particle accelerators can be divided in two categories

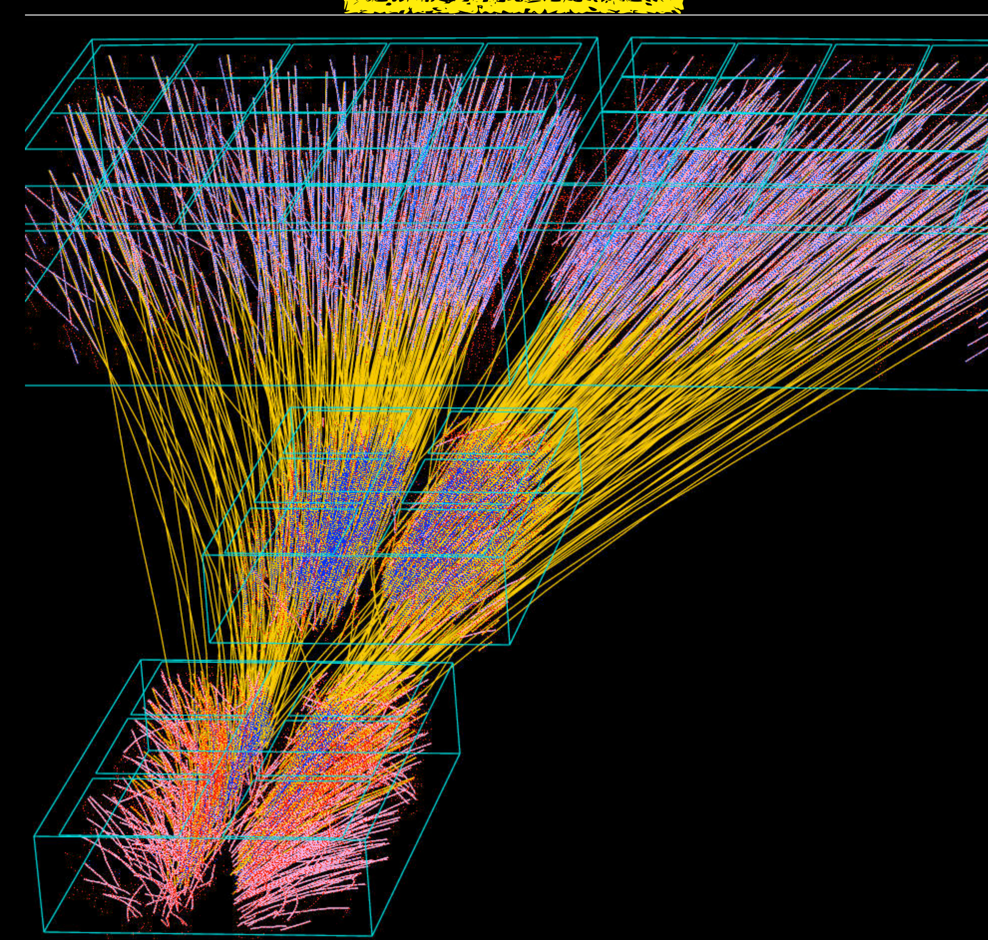
  - colliding beams machines where two beams of particles are accelerated at high velocities, circulate in opposite directions and are brought to collision

  - fixed-target experiments where a single beam is accelerated at high velocities and collides into a stationary target

Colliding beams



Fixed target



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Basic considerations

$$\sqrt{s} = \sqrt{(E_1+E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2}$$

- In a particle collider the centre-of-mass energy is all available for particle production
  - Favoured for study of massive particles
    - production and eventual discovery of the carriers of the weak force Z^0 and $W^{\pm}$, or even the Higgs boson discovered in 2012 at CERN

- In a fixed target experiment, momentum conservation implies that the final state particles are always produced with significant kinetic energy and they are produced mainly in the so-called forward region

Colliding systems

Collider	Laboratory	Colliding system	Data of operation	$\sqrt{s}$/GeV	Luminosity/cm^{-2}s^{-1}
PEP–B	SLAC	e^+e^-	1999–2008	10.5	1.2×10^{34}
KEKB	KEK	e^+e^-	1999–2010	10.6	12.1×10^{34}
LEP	CERN	e^+e^-	1989–2000	90–209	10^{32}
HERA	DESY	e^+p/e^-p	1992–2007	320	8×10^{31}
Tevatron	Fermilab	p$\overline{\text{p}}$	1987–2002	1960	4×10^{32}
LHC	CERN	pp/pPb/PbPb	2009–today	14000/5000/5000	10^{34} (for pp)

- Only stable charged particles can be accelerated to high energies
  - limiting the possibilities for colliding configurations to
    - e^+e^- colliders,
    - hadron colliders (e.g. pp, or pbar-p),
    - e^+p or e^-p colliders
    - heavy-ion colliders (e.g. Pb-Pb)

Luminosity (1)

- Luminosity determines the rate of events
  - For a given process the number of interactions is the product of the luminosity integrated over the lifetime of the operation of the machine and the cross-section (σ) of the process in question

$$N=\sigma \int L(t)dt$$

- The cross-section is a measure of the probability for a given interaction to occur
- In order to convert the observed number of events of a particular type into the cross-section of a given process, the integrated luminosity needs to be estimated.

Luminosity (2)

- Typically the particles in an accelerator are grouped in bunches that are brought into collisions at one or more interaction points

  - As an example, at the LHC the bunches are separated by 25ns corresponding to a collision frequency of f = 40MHz

  - The instantaneous luminosity of the machine can be expressed in terms of
    - the number of particles in the colliding bunches, n_1 and n_2,
    - the frequency at which the bunches collide,
    - the root-mean-square (rms) of the horizontal and vertical beam sizes, σ_x and σ_y

  - Assuming that the beams have a Gaussian profile and collide head-on, the instantaneous luminosity is given by

$$L = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

CERN LHC


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km