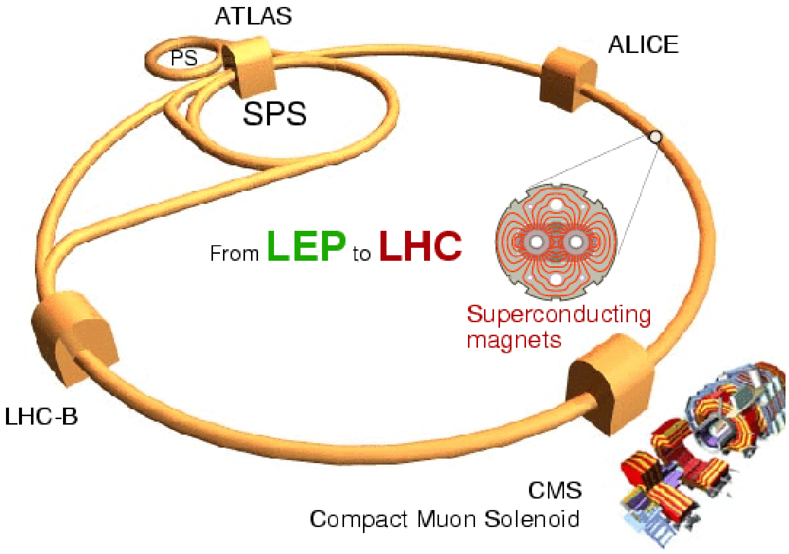
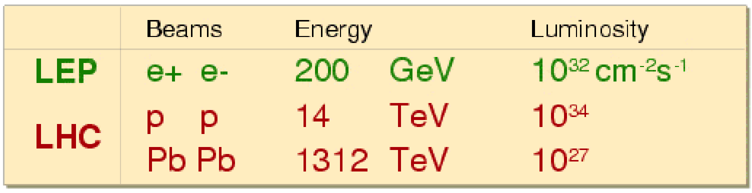
# III. Experimental methods

Before 1950s, cosmic rays were the source of high energy particles, and cloud chambers and photo-emulsions were the means to detect them.

The quest for heavier particles and more precise measurements lead to the increasing importance of *accelerators* to produce particles and more complicated *detectors* to observe them.





| | Beams | Energy | | Luminosity |
|---|---|---|---|---|
| **LEP** | e+ e- | 200 | GeV | $10^{32}$ cm$^{-2}$s$^{-1}$ |
| **LHC** | p p | 14 | TeV | $10^{34}$ |
| | Pb Pb | 1312 | TeV | $10^{27}$ |

Figure 18: A future accelerator

# Accelerators

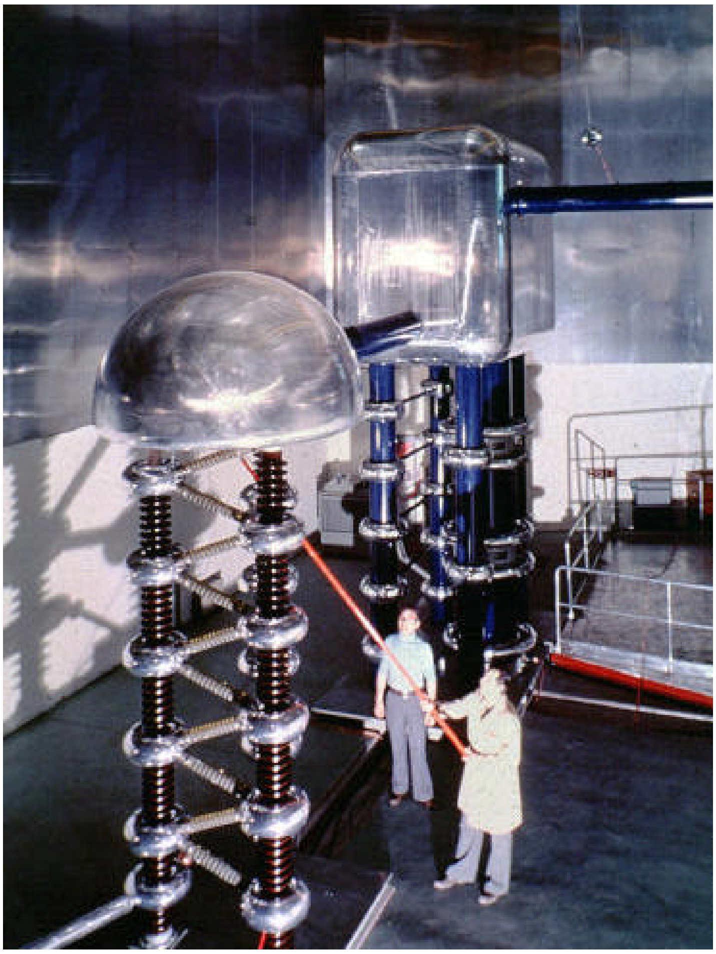


Figure 19: The Cockroft-Walton generator at CERN: accelerates particles by an electrostatic field

⇨ Basic idea of all accelerators: apply a voltage to accelerate particles

Main varieties of accelerators are:

– Linear accelerators ( *“linacs”* )

– Cyclic accelerators (*“cyclotrons”*, *“synchrotrons”* )

# Linear accelerators

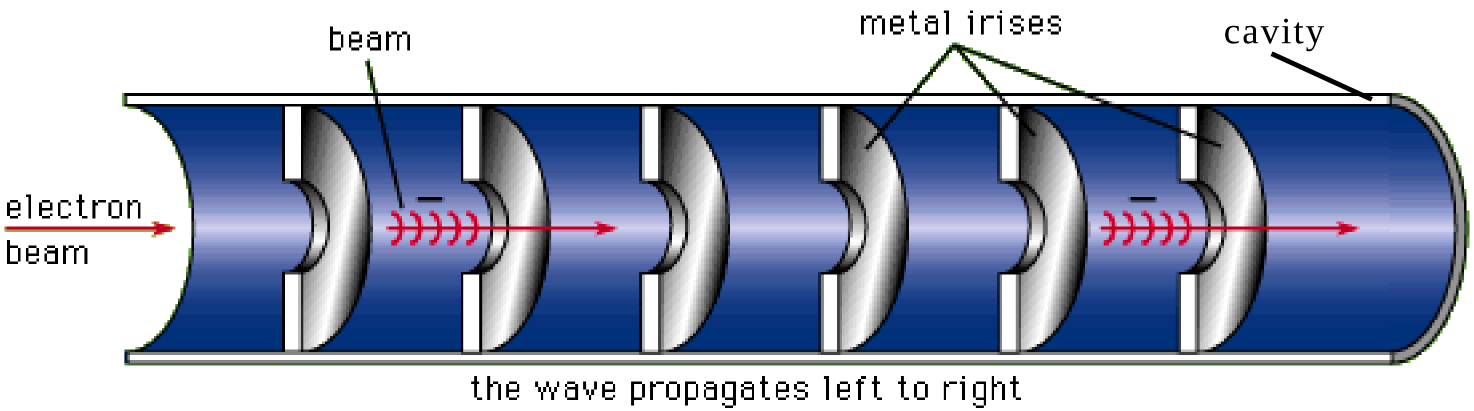


Figure 20: A traveling-wave linear accelerator schematics

❖Linacs are used mostly to accelerate electrons

– Electrons are accelerated along a sequence of cylindrical vacuum cavities

– Inside cavities, an electromagnetic field is created with a frequency near 3,000 MHz (radio-frequency), the electric field along the beam axis ($\overline{F}=q\overline{E}$)

– Electrons arrive into each cavity at the same phase as the electric wave

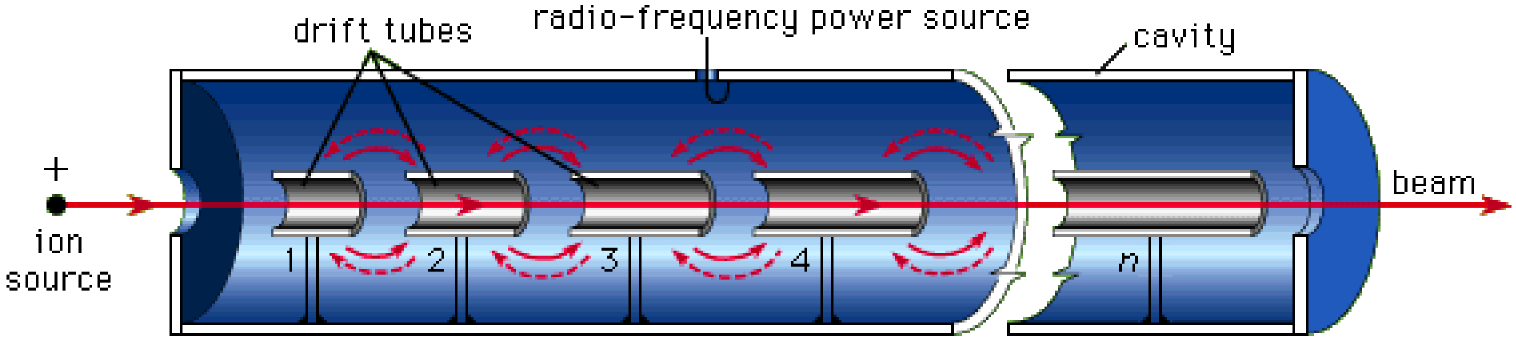


Figure 21: Standing-wave linac

❖Standing-wave linacs are used to accelerate heavier particles, like protons

– Typical frequency of the field is about 200 MHz

– Drift tubes screen particles from the electromagnetic field for the periods when the field has decelerating effect

– Lengths of drift tubes are proportional to particles’ speed

# Cyclic accelerators.

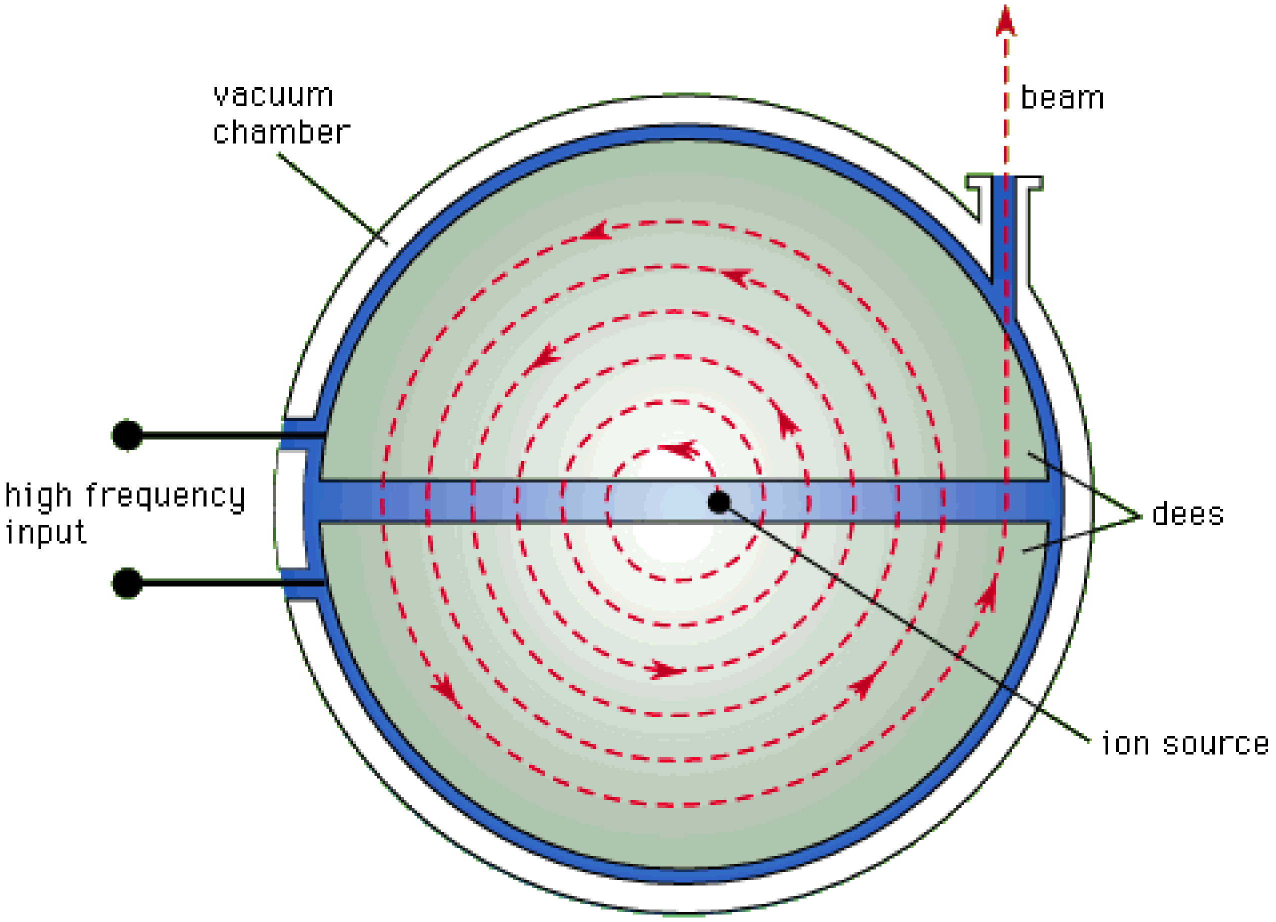


Figure 22: Cyclotron, the first resonance accelerator. Maximal energy for protons 25 MeV.

– $\overline{F}=q(\overline{E}+\overline{v}\times\overline{B})$ : Particle is accelerated by the high frequency field $\overline{E}$ between the dees ($\overline{F}=q\overline{E}$)

– The vacuum chamber is placed inside a magnetic field $\overline{B}$, perpendicular to the rotation plane

– Dees ("D") are empty "boxes" working as electrodes; in the dees $\overline{E}=0$ ($\overline{F}=q\,\overline{v}\times\overline{B}$)

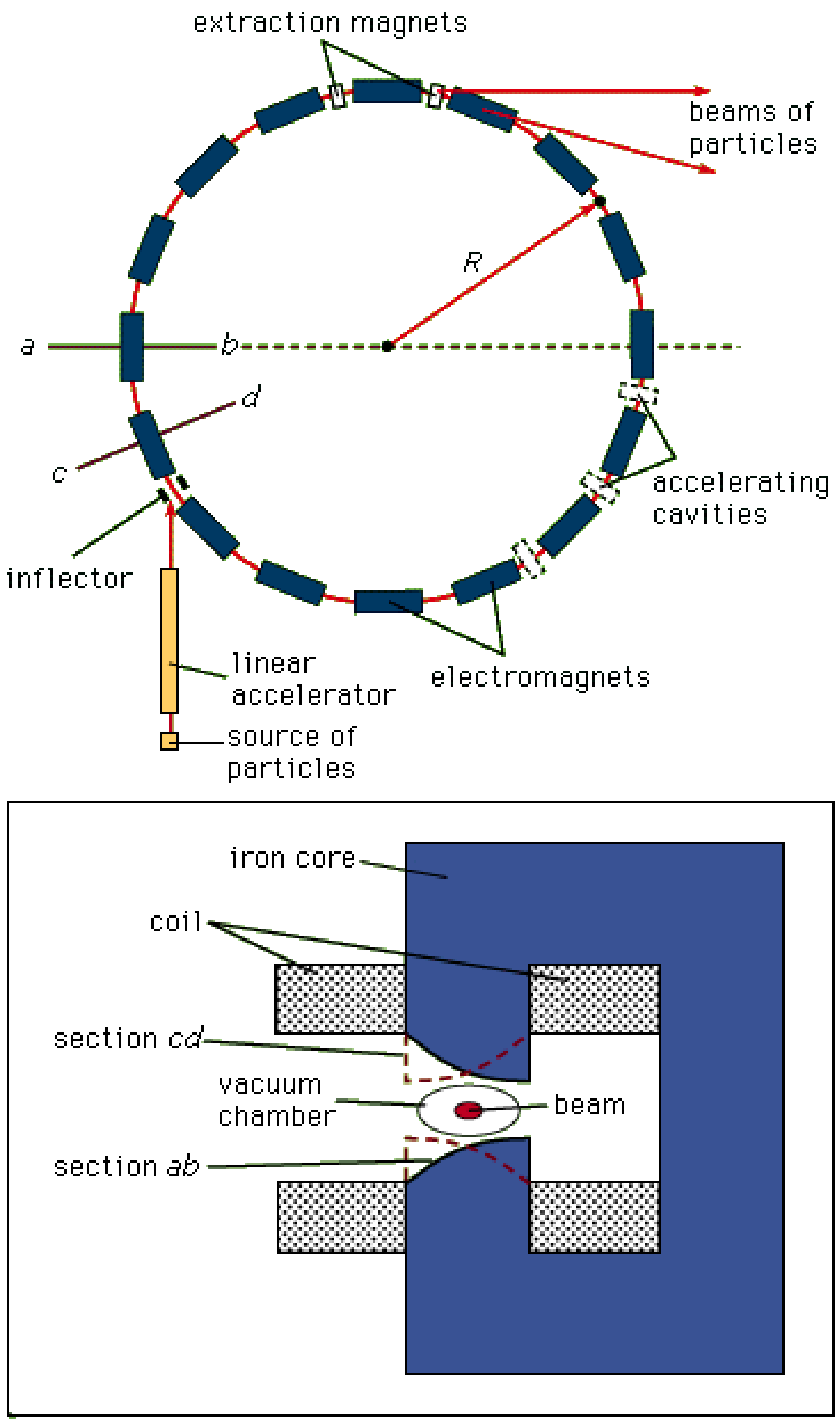


Figure 23: Schematic layout of a synchrotron

– Synchrotrons are the most widely used circular accelerators

– Beam of particles is constrained in a circular path by bending dipole magnets ($\overline{F}=q\,\overline{v}\times\overline{B}$)

– Accelerating cavities are placed along the ring ($\overline{F}=q\overline{E}$)

– Charged particles which travel in a circular orbit with relativistic speeds emit *synchrotron radiation*

Amount of energy radiated per turn is:

$$\Delta E = \frac{q^2\beta^3\gamma^4}{3\varepsilon_0\rho} \tag{31}$$

Here $q$ is electric charge of a particle, $\beta\equiv v/c$ , $\gamma\equiv(1-\beta^2)^{-1/2}$, and $\rho$ is the radius of the orbit.

⇨ For relativistic particles $\gamma=E/mc^2$ $\Rightarrow$ energy loss increases as $E^4/m^4$ , becoming very significant for high-energy light particles (electrons)

⇨ Radio-frequency power is limited $\Rightarrow$ electron synchrotrons must become extremely large (large $\rho$) to compensate for the synchrotron radiation.

⇨ From the standard expression for the centrifugal force, momentum of the particle with the unit charge ($q=1$) in a synchrotron is

$$p = 0.3B\rho \; ([B]=T, [r]=m, [p]=GeV/c)$$

Hence the magnetic field $B$ has to increase, given that ρ must be constant and the goal is to increase momentum.

⇨ Maximal momentum is therefore limited by both the maximal available magnetic field and the size of the ring.

❖To keep particles well contained inside the beam pipe and to achieve the stable orbit, particles are accelerated in *bunches*, synchronized with the radio-frequency field

Analogously to linacs, all particles in a bunch have to move in phase with the radio-frequency field.

Requirement of precise synchronisation, however, is not very tight: particles behind the radio-frequency phase will receive lower momentum increase, and other way around.

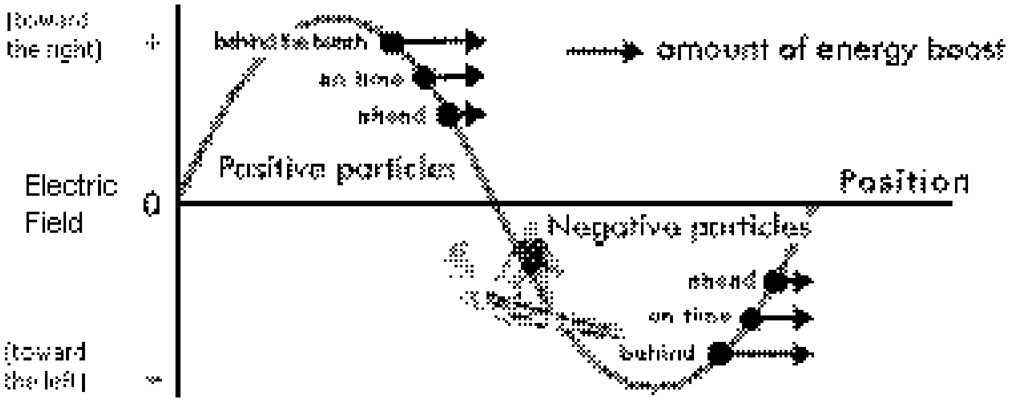


Figure 24: Effect of the electric field onto the particles in accelerator cavities

⇨ Therefore all particles in a bunch stay basically on the same orbit, slightly oscillating

To keep particle beams focused, quadrupole and sextupole magnets are placed along the ring and act like optical lenses

Depending on whether the beam is shooting into a stationary ("fixed") target, or is colliding with another beam, both linear and cyclic accelerators are divided into two types:

- ❖*"fixed-target"* machines
- ❖*"colliders"* (*"storage rings"* in case of cyclic machines)

Some fixed target accelerators:

| **Machine** | **Type** | **Particles** | **$E_{beam}$ (GeV)** |
|---|---|---|---|
| **Tevatron II**<br>**Fermilab, Illinois, USA** | synchrotron | p | 1000 |
| **SPS**<br>**CERN, Geneva, Switzerland** | synchrotron | p | 450 |
| **SLAC**<br>**Stanford, California** | linac | $e^-$ | 25 |

Much higher energies are achieved for protons compared to electrons, due to smaller losses caused by synchrotron radiation.

Fixed-target machines can be used to produce secondary beams of neutral or unstable particles.

- Centre-of-mass energy, i.e. energy available for particle production during the collision of a beam of energy $E_L$ with a target is :

$$E_{CM} = \sqrt{m_b^2c^4 + m_t^2c^4 + 2m_tc^2E_L} \qquad (32)$$

Here $m_b$ and $m_t$ are masses of the beam and target particles. $E_{CM}$ increases as square-root of $E_L$.

Higher centre-of-mass energies can be achieved by colliding two beams of energies $E_A$ and $E_B$ (at an optional crossing angle $\theta$), so that

$$E_{CM}^2 = 2E_AE_B(1 + \cos\theta) \qquad (33)$$

Some colliders:

| **Machine** | **Start-end** | **Particles** | **$E_{beam}$ (GeV)** |
|---|---|---|---|
| **KEKB**, KEK, Tokyo, Japan | 1999- | $e^-$, $e^+$ | 8, 3.5 |
| **PEP-II**, SLAC, California, USA | 1999- | $e^-$, $e^+$ | 9, 3.1 |
| **LEP**, CERN, Geneva, Switzerland | 1989-2000 | $e^-$, $e^+$ | 105 |
| **HERA**, Hamburg, Germany | 1992- | $e^-$, p | 30, 920 |
| **Tevatron II**, Fermilab, Illinois, USA | 1987- | p, $\bar{p}$ | 1000 |
| **LHC**, CERN, Geneva, Switzerland | 2007- | p, p | 7000 |

# Particle interactions with matter

⇨ All particle detecting techniques are based on the interactions of particles with different materials

## *Short-range interaction with nuclei*

❖Probability of a particle to interact (with a nucleus or another particle) is called *cross-section*.

Cross-sections are normally measured in *millibarns*:

$$1\ mb \equiv 10^{-31}\ m^2$$

Total cross-section of a reaction is sum over all possible processes

There are two main kinds of scattering processes:

– *elastic scattering*: only momenta of incident particles are changed, for example, $\pi^- p \to \pi^- p$

– *inelastic scattering*: final state particles differ from those in initial state, like in $\pi^- p \to K^0 \Lambda$

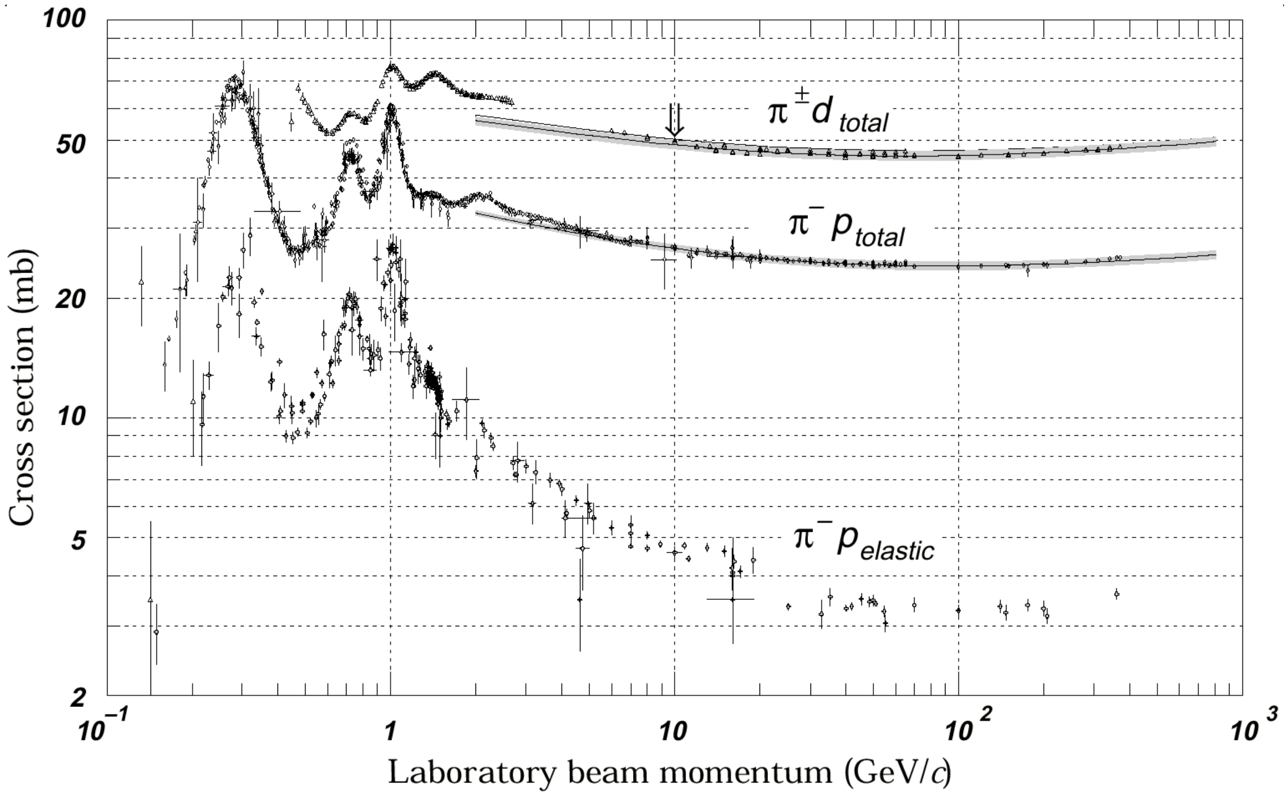


Figure 25: Cross sections of $\pi^-$ on a fixed proton target

For hadron-hadron scattering, cross-sections are of the same order with the geometrical "cross-sections" of hadrons: assuming their sizes are of order $r = 1\ fm \equiv 10^{-15}\ m \Rightarrow \pi r^2 \approx 30\ mb$

For complex nuclei, obviously, cross-sections are bigger, and elastic scattering on one of the nucleons can lead to nuclear excitation or break-up – so-called *quasi-elastic scattering*.

Knowing cross-sections and number of nuclei per unit volume in a given material $n$, one can introduce two important characteristics:

*nuclear collision length = mean free path between collisions*: $l_c \equiv 1/n\sigma_{\mathrm{tot}}$

*nuclear absorption length = mean free path between inelastic collisions*: $l_a \equiv 1/n\sigma_{\mathrm{inel}}$

At high energies, mainly hadrons participate in short-range nuclear interactions.

Neutrinos and photons have much smaller cross-sections of interactions with nuclei, since former interact only weakly and latter -- only electromagnetically.

## *Ionization energy losses*

- ⇨ Important for all charged particles.
- ⇨ Predominantly due to Coulomb scattering of particles from atomic electrons.

Energy loss per travelled distance : $dE/dx$

Bethe-Bloch formula for spin-0 bosons with charge ±e ($\pi^+,\pi^-,K^+,K^-$):

$$-\frac{dE}{dx} = \frac{Dn_e}{\beta^2}\left[ln\left(\left(\frac{2mc^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta(\gamma)}{2}\right)\right] \quad (34)$$

$$D = \frac{4\pi\alpha^2\hbar^2}{m} = 5{,}1\times10^{-25}\ MeV\ cm^2$$

In Equation (34), $\beta = v/c$=velocity ($p = mv$).

Figure 26: At low β, $dE/dx$ is proportional to $1/\beta^2$. At high β, $dE/dx$ proportional to $ln(\beta)$

$n_e$, $I$ and $\delta(\gamma)$ are constants which are characteristic to the medium:

- ❖$n_e$ is the electron density, $n_e = \rho N_A Z/\tilde{A}$, where ρ is the mass density of the medium and $\tilde{A}$ is its atomic weight. Hence, energy loss is strongly *proportional to the density* of the medium

- ❖$I$ is the mean ionization potential, $I \approx 10Z\ eV$ for $Z > 20$

- ❖$\delta(\gamma)$ is a dielectric screening correction, important only for very energetic particles.

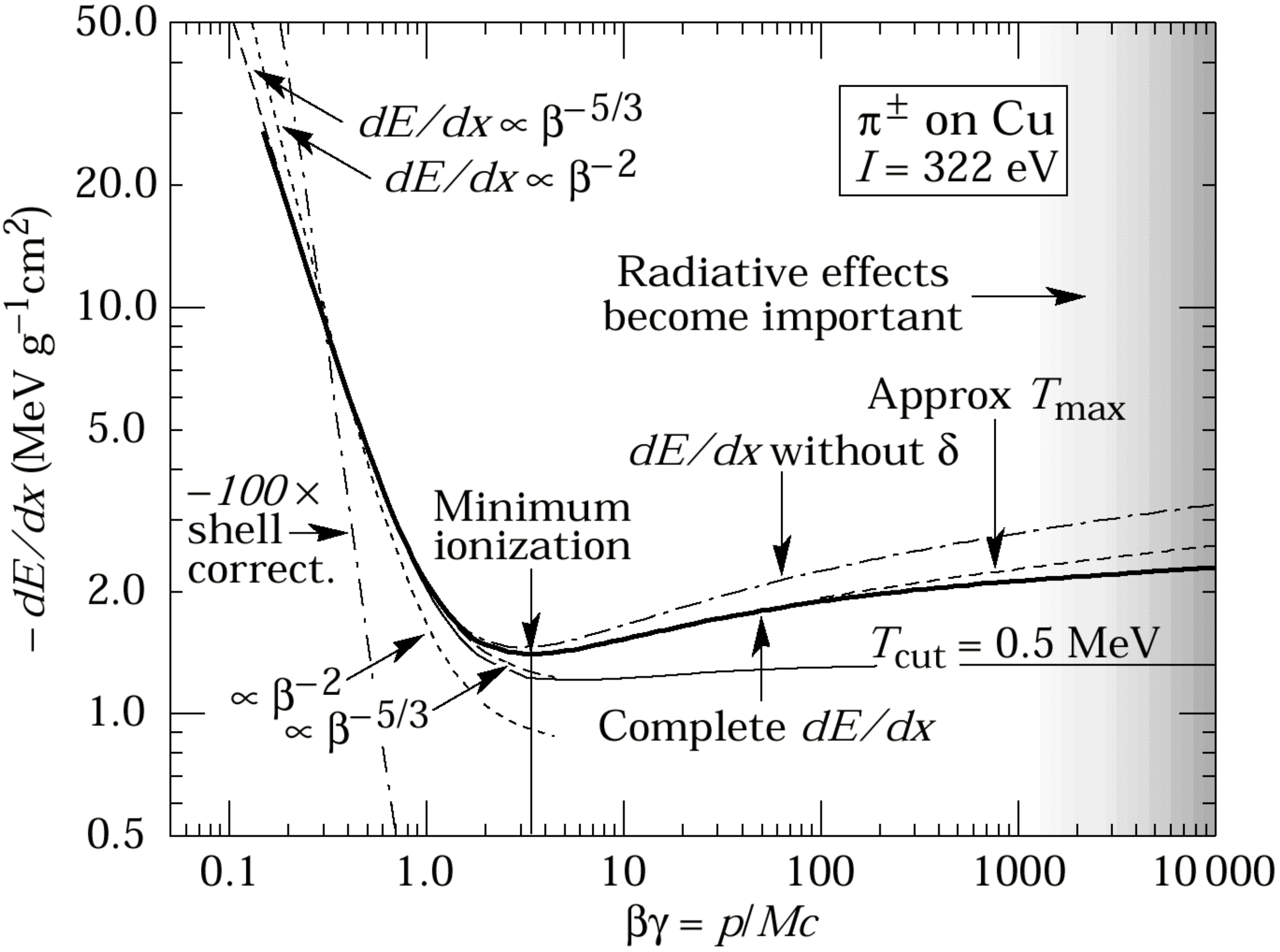


Figure 26: Energy loss rate for pions in copper

## *Radiation energy losses*

⇨ Electric field of a nucleus accelerates or decelerates particles, causing them to radiate photons, hence, lose energy : *bremsstrahlung*

Bremsstrahlung is an important source of energy loss for light particles like electrons. It is, however, significant only for high-energy electrons/positrons.

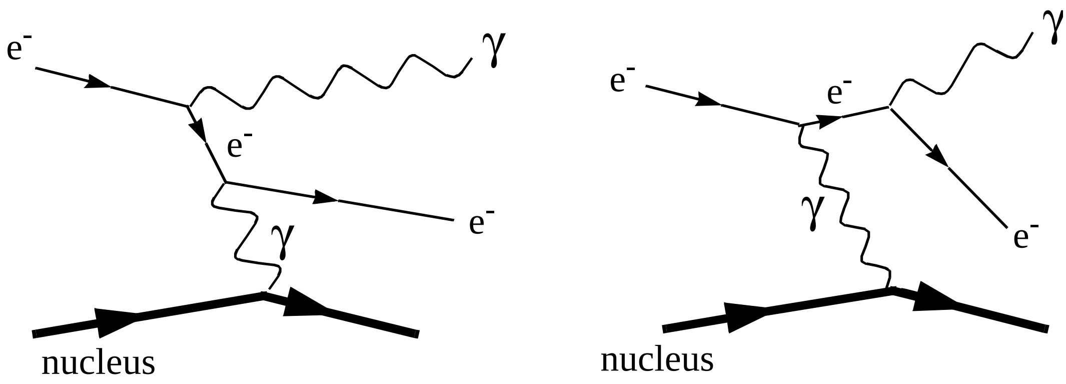


Figure 27: The dominant Feynman diagrams for the bremsstrahlung process e$^-$+ (Z,A) → e$^-$+ γ + (Z,A)

❖Contribution to bremsstrahlung from the field of nucleus is of order $Z^2\alpha^3$ , and from atomic electrons – of order $Z\alpha^3$ ($\alpha^3$ from each electron).

❖For relativistic electrons, average rate of bremsstrahlung energy loss is given by:

$$-\frac{dE}{dx} = \frac{E}{L_R} \tag{35}$$

The constant $L_R$ is called the radiation length:

$$\frac{1}{L_R} = 4\left(\frac{\hbar}{mc}\right)^2 Z(Z+1)\alpha^3 n_a \ln\left(\frac{183}{Z^{1/3}}\right) \tag{36}$$

In Equation (36), $n_a$ is the density of atoms per $cm^3$ in medium.

⇨ Radiation length is the average thickness of material which reduces the mean energy of the particle (electron or positron) by a factor $e$.

## *Interactions of photons in matter*

Main contributing processes to the total cross-section of photon interaction with atom are (see Fig.28):

1) Photoelectric effect ($\sigma_{p.e.}$)

2) Compton effect ($\sigma_{incoh}$)

3) Pair production in nuclear and electron field ($\kappa_N$ and $\kappa_e$)

At high energies, pair production is the dominant process: $\sigma_{pair}=7/9 n_a L_R$ , and number of photons travelled distance $x$ in the matter is

$$I(x) = I_0 e^{-7x/9L_R}$$

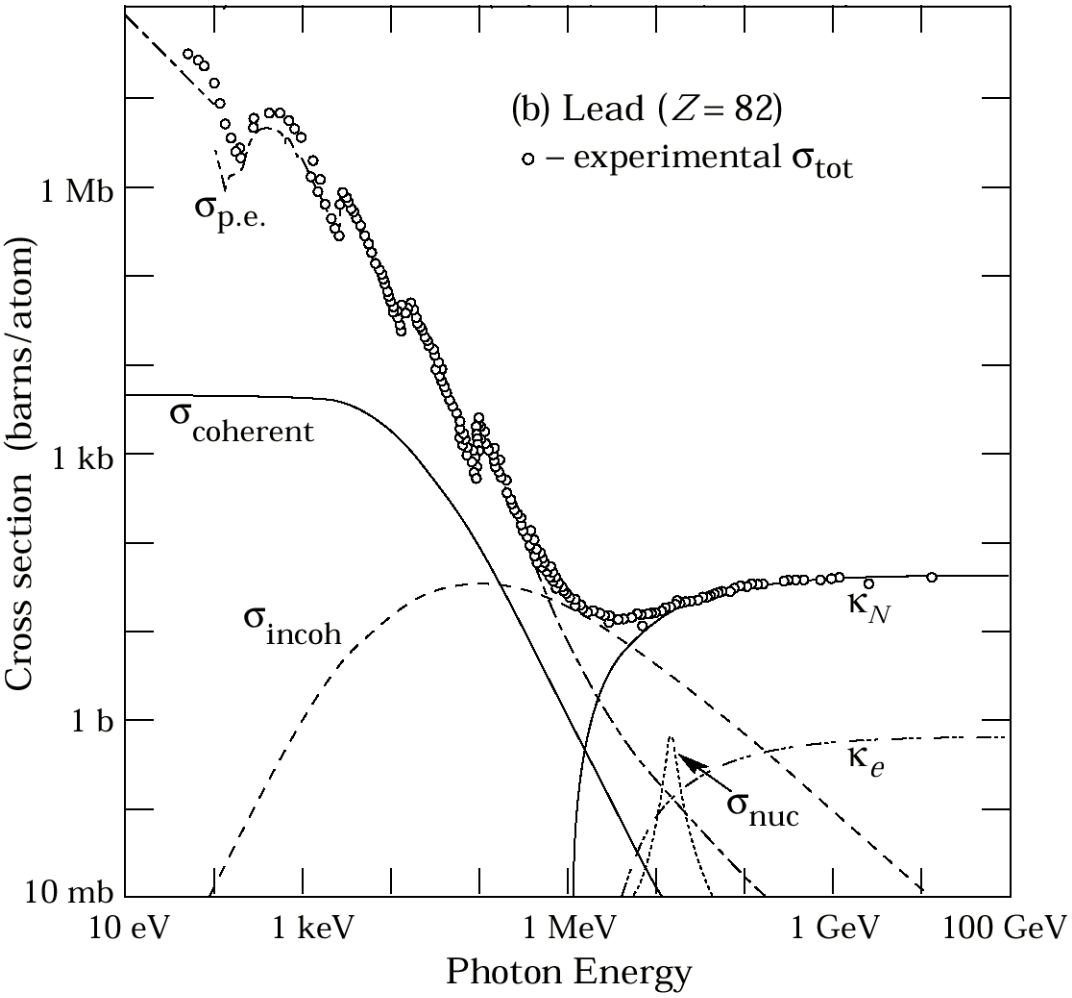


Figure 28: Photon interaction cross-section on a lead atom

Note that the pair production is possible only for photon energies $E>2m_e$ ($E>1\ MeV$).

# Particle detectors

Main types of particle detectors:

1) Tracking devices – coordinate measurements
2) Calorimeters – energy measurements
3) Time resolution counters
4) Particle identification devices
5) Spectrometers - momentum measurements

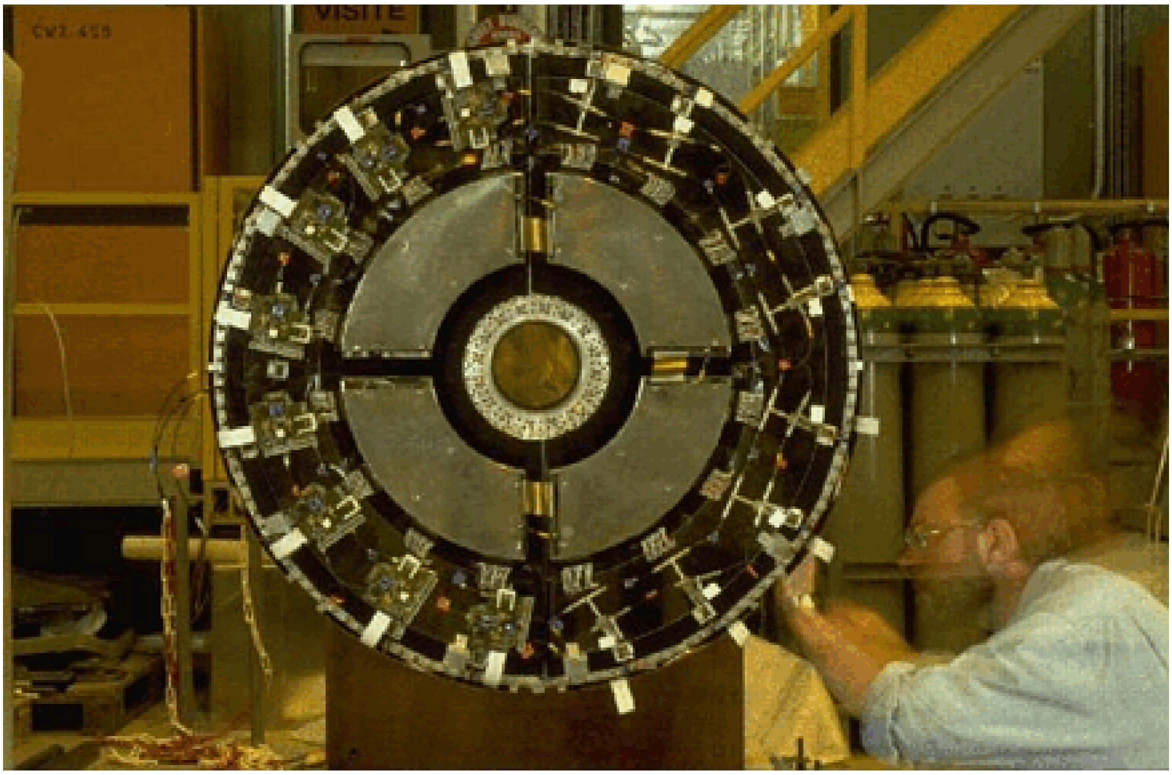


Figure 29: STIC detector for the DELPHI experiment

# Position measurement

⇨ Main principle: ionization products are either visualized (as in photoemulsions) or collected on electrodes to produce an electronic signal

Basic requirements of high-energy experiments:

– High spatial resolution (∝ 10-100 μm)

– Possibilities to register particles synchronously with a high rate (good *triggering*)

To fulfil the latter, electronic signal pick-up is necessary, therefore photoemulsions and bubble chambers were abandoned...

❖Modern tracking detectors fall in two major categories:

a) Gaseous detectors (“*gas chambers*”), resolution ~100-500 μm

b) Semiconductor detectors, resolution ~ 5μm

# Proportional and drift chambers

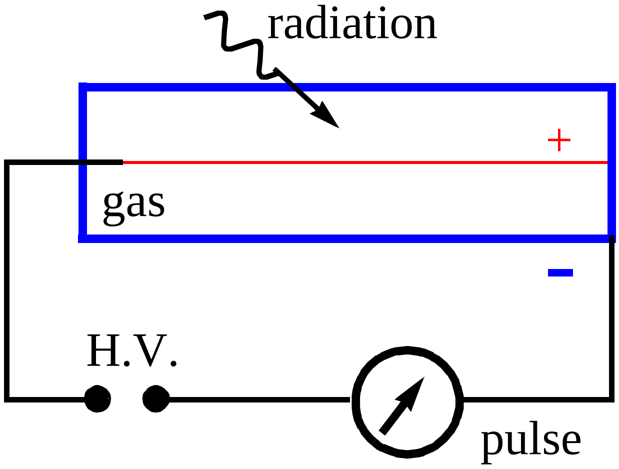


Figure 30: Basic scheme of a wire chamber

A simplest proportional chamber:

– A conducting chamber, filled with a gas mixture and serving as a cathode

– A wire inside serves as an anode

– A charged particles ionizes gas ⇒ electron-ion pairs, drift towards anode/cathode. The field accelerates the electrons ⇒ secondary electron-ion pairs ⇒ avalance of electrons ⇒ pulse in the anode. Amplification is $\propto 10^5$ for voltage of $10^4$-$10^5$ $V/cm$.

Several anode wires ⇒ coordinate measurement (Multi-Wire Proportional Chamber, MWPC)

# Alternative to MWPC : *drift chambers*

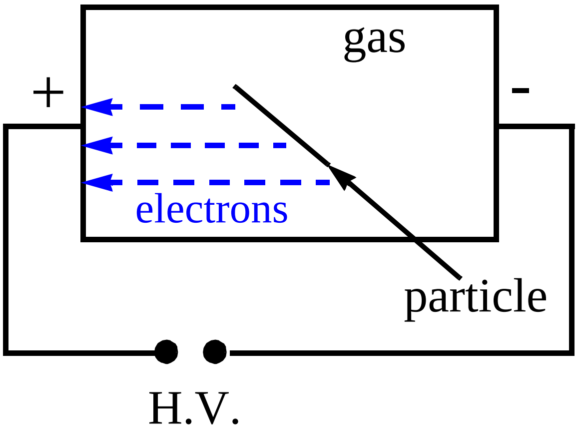


Figure 31: Basic scheme of a drift chamber

– Ionization electrons produced along the particle passage arrive to the pick-up anode at different times $t_1, t_2, t_3, \ldots$

– knowing (from other detectors) the time of particle's arrival $t_0$ and field in the chamber, one can calculate coordinates of the track $l_1, l_2, l_3, \ldots$

*Streamer detectors* are wire chambers in which secondary ionization is not limited and develops into moving plasmas = *streamers*

If H.V. pulse in a wire chamber is long enough, a spark will occur, which is achieved in *spark chambers*

## *Semiconductor detectors*

⇨ In semiconducting materials, like silicon, ionizing particles produce electron-hole pair, and number of these pairs is proportional to energy loss by particles

Silicon detectors are p-n junction diodes operated at reverse bias (typically 50-100 $V$, low operating voltage). Liberated charge drifts to the pick-up electrodes etched on the surface. Silicon detectors have far better resolution than gas detectors.

❖Superior resolution (few $\mu m$), small size, small power consumption, fast signals.

❖Radiation damages can be circumvented by using radiation-hard manufacturing processes, approriate handling (e.g. cooling) and by using very thin detectors.

## *Calorimeters*

⇨ To measure energy (and position) of the particle, calorimeters use absorbing material, in which the original particle is absorbed.

⇨ Signals produced in calorimeters are proportional to the energy of the incoming particle.

⇨ During the absorption process, particle interacts with the material of the calorimeter and produces a secondary shower.

⇨ Since electromagnetic and hadronic showers are somewhat different, there are two corresponding types of calorimeters

## *Electromagnetic calorimeters (electron and g energy measurement)*

– The dominant energy loss for high-energy electrons (or positrons) is bremsstrahlung: $e^- \to e^- \gamma$

– Photons produced via bremsstrahlung produce $e^+e^-$ pairs and are thus absorbed again: $\gamma \to e^+e^-$

– An initial electron thus produces a cascade of photons and $e^+e^-$ pairs, until its energy falls under the bremsstrahlung threshold of $E_C \approx 600\ MeV/Z$

❖A calorimeter has to be large enough to absorb all the possible energy of the incoming particle.

Main assumptions for electromagnetic showers:

a) Each electron with $E>E_C$ travels one radiation length and radiates a photon with $E_\gamma=E/2$

b) Each photon with $E_\gamma>E_C$ travels one radiation length and creates an $e^+e^-$ pair, which shares equally $E_\gamma$

c) Electrons with $E<E_C$ cease to radiate; for $E>E_C$ ionization losses are negligible

These considerations lead to the expression:

$$t_{max} = \frac{\ln(E_0/E_C)}{\ln 2} \tag{37}$$

where $t_{max}$ is number of radiation lengths needed to stop the electron of energy $E_0$.

Electromagnetic calorimeters can be, for example, lead-glass (crystal) blocks collecting the light emitted by showers, or a drift chamber interlayed with heavy absorber material (lead).

## *Hadron calorimeters (hadron energy measurement: pions, kaon, protons, neutrons)*

- ❖Hadronic showers are similar to the electromagnetic ones, but absorption length is larger than the radiation length of electromagnetic showers since hadrons interact in the material through nuclear interactions.
- ❖Also, some contributions to the total absorption may not lead to a signal in the detector (e.g., nuclear excitations or neutrons)

Main characteristics of a hadron calorimeters are:

a) It has to be thicker than electromagnetic one

b) Layers of $^{238}$U can be introduced to compensate for energy losses (low-energy neutrons cause fission)

c) energy resolution of hadron calorimeters is generally rather poor

Hadron calorimeter is usually a set of MWPC's or streamer tubes, interlayed with thick iron absorber

## Scintillation counters

⇨ Scintillation counters are widely used to detect the passage of charged particles through an experimental setup and to measure particle's "*time-of-flight*" (TOF).

⇨ Scintillators are materials (crystals or organic=plastic) in which ionizing particles produce visible light without losing much of its energy

❖The light is guided down to photomultipliers and is being converted to a short electronic pulse.

## Particle identification

– Knowing momentum of particle is not enough to identify it, hence complementary information is needed.

– For low-energy particles ($E<1\ GeV$), TOF counters can provide this complementary data.

– Energy loss rate $dE/dx$ depends on particle mass for energies below $\approx 2\ GeV$ ($1/\beta^2$ region)

⇨ The most reliable particle identification device: *Cherenkov counters*

– In certain media, energetic charged particles move with velocities higher that the speed of light in these media

– Excited atoms along the path of the particle emit coherent photons at a characteristic angle $\theta_C$ to the direction of motion

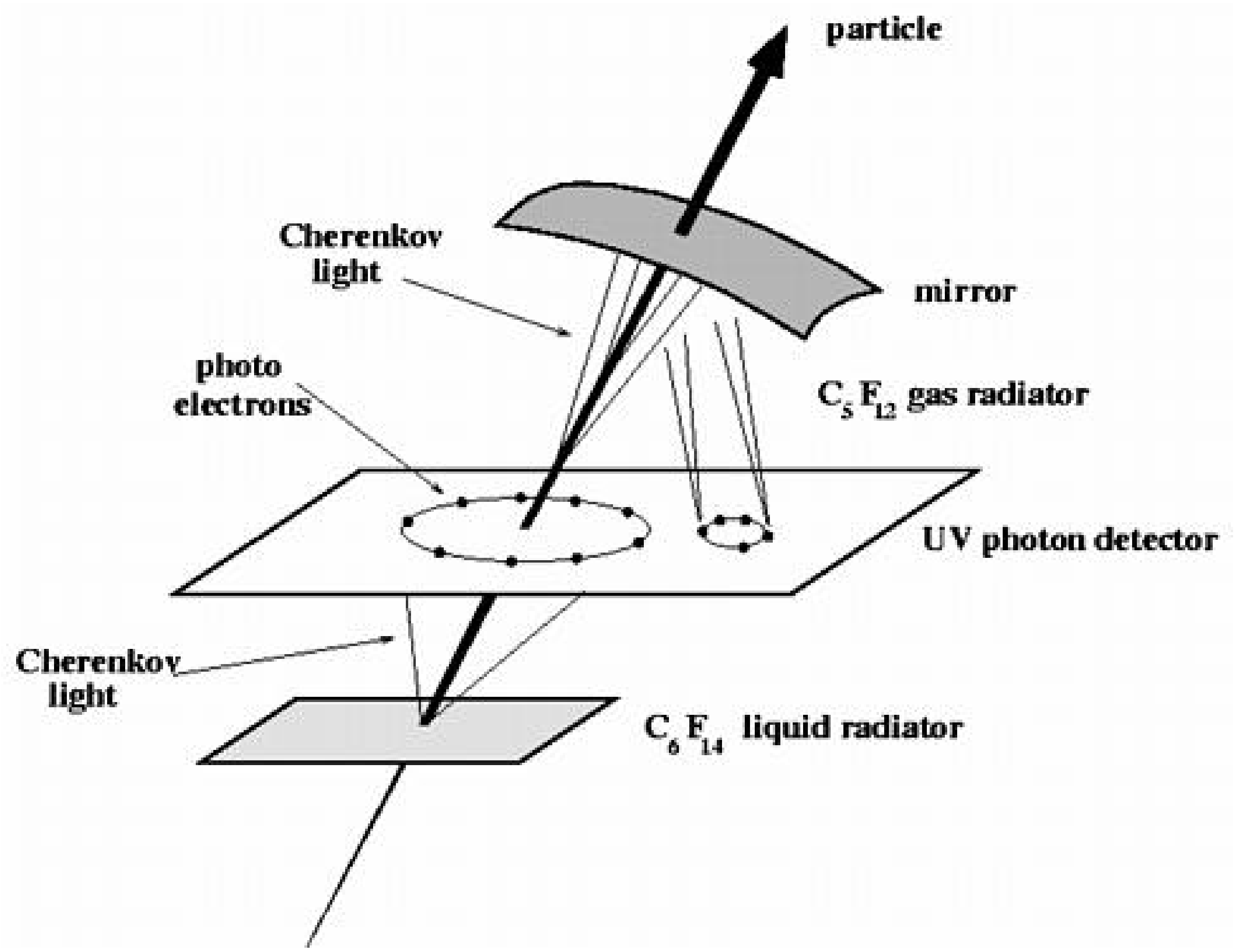


Figure 32: Cherenkov effect in the DELPHI RICH detector

The angle $\theta_C$ depends on the refractive index of the medium $n$ and on the particle's velocity $v$:

$$\cos\theta_C = c / vn \tag{38}$$

Hence, measuring $\theta_C$ , the velocity of the particle can be easily derived, and the identification performed: $p$ is obtained from another tracking device, $v$ from Cherenkov counter → $m=p/v$.

Cherenkov counters can be used for particle identification in a large momentum range, typically from few $GeV$ up to about 50 $GeV$.

## *Transition radiation measurements*

– In ultra-high energy region, particles velocities do not differ very much

– Whenever a charged particle traverses a border between two media with different dielectric properties, a *transition radiation* occurs

– Intensity of emitted radiation is sensitive to the particle's energy $E=\gamma mc^2$.

– Transition radiation occurs only if $\gamma > 1000$, which means $E/m > 1000$.

Therefore transition radiation measurements are particularly useful for separating electrons from other particles: for electrons, $\gamma = 1000$ for $E = 0.5\ GeV$. For pions, $\gamma = 1000$ for $E = 135\ GeV \Rightarrow e/p$ separation between 0.5 and 135 $GeV$.

## Spectrometers

❖Momenta of particles are measured by the curvature of the track in a magnetic field: $p = 0.3B\rho$ ($[B]=T, [r]=m, [p]=GeV/c$), where ρ is curvature, $B$ is magnetic field.

Spectrometers are tracking detectors placed inside a magnet, providing momentum information.

In collider experiments, no special spectrometers are arranged, but all the tracking setup is contained inside a solenoidal magnet.

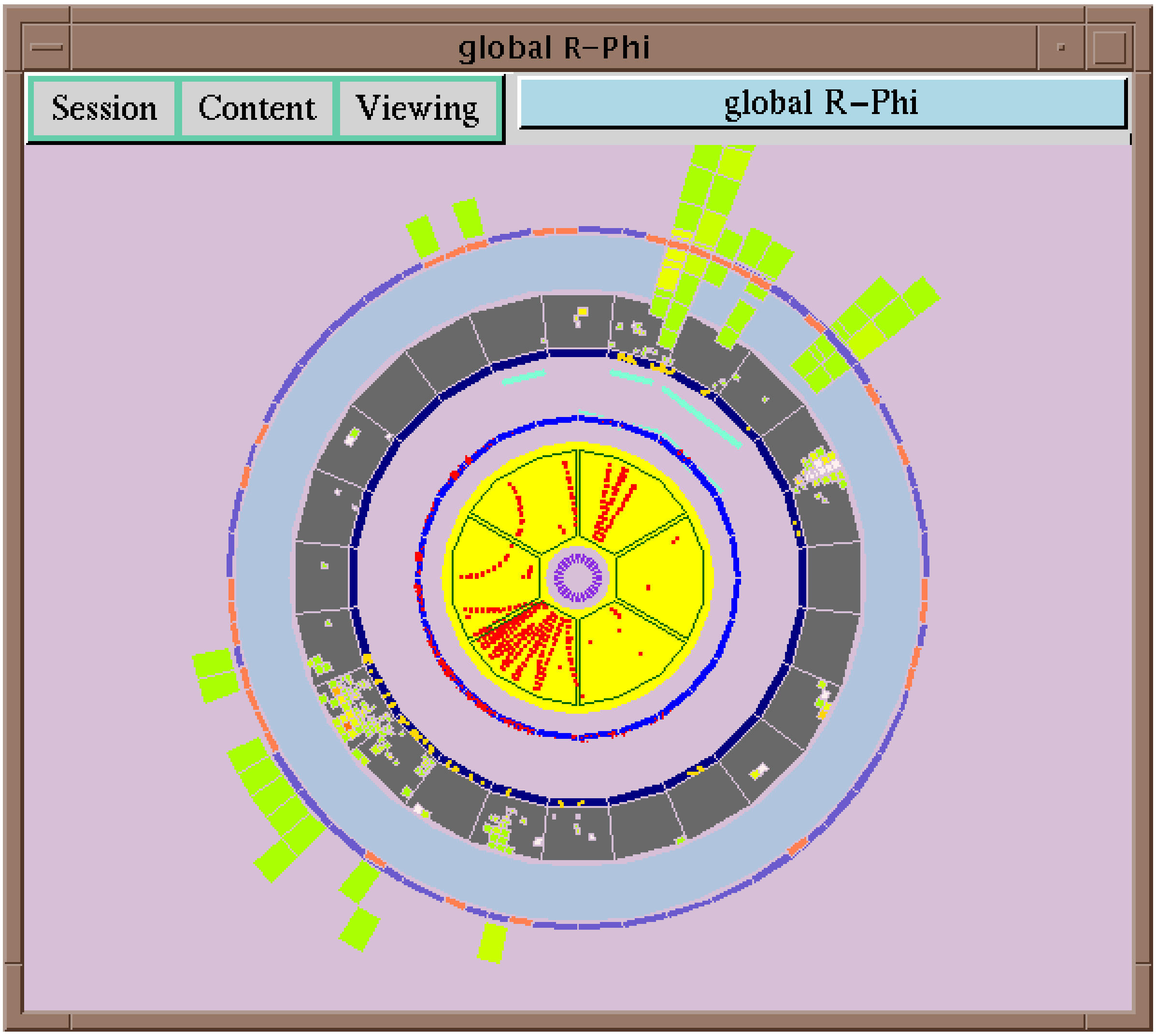


Figure 33: A hadronic event as seen by the DELPHI detector

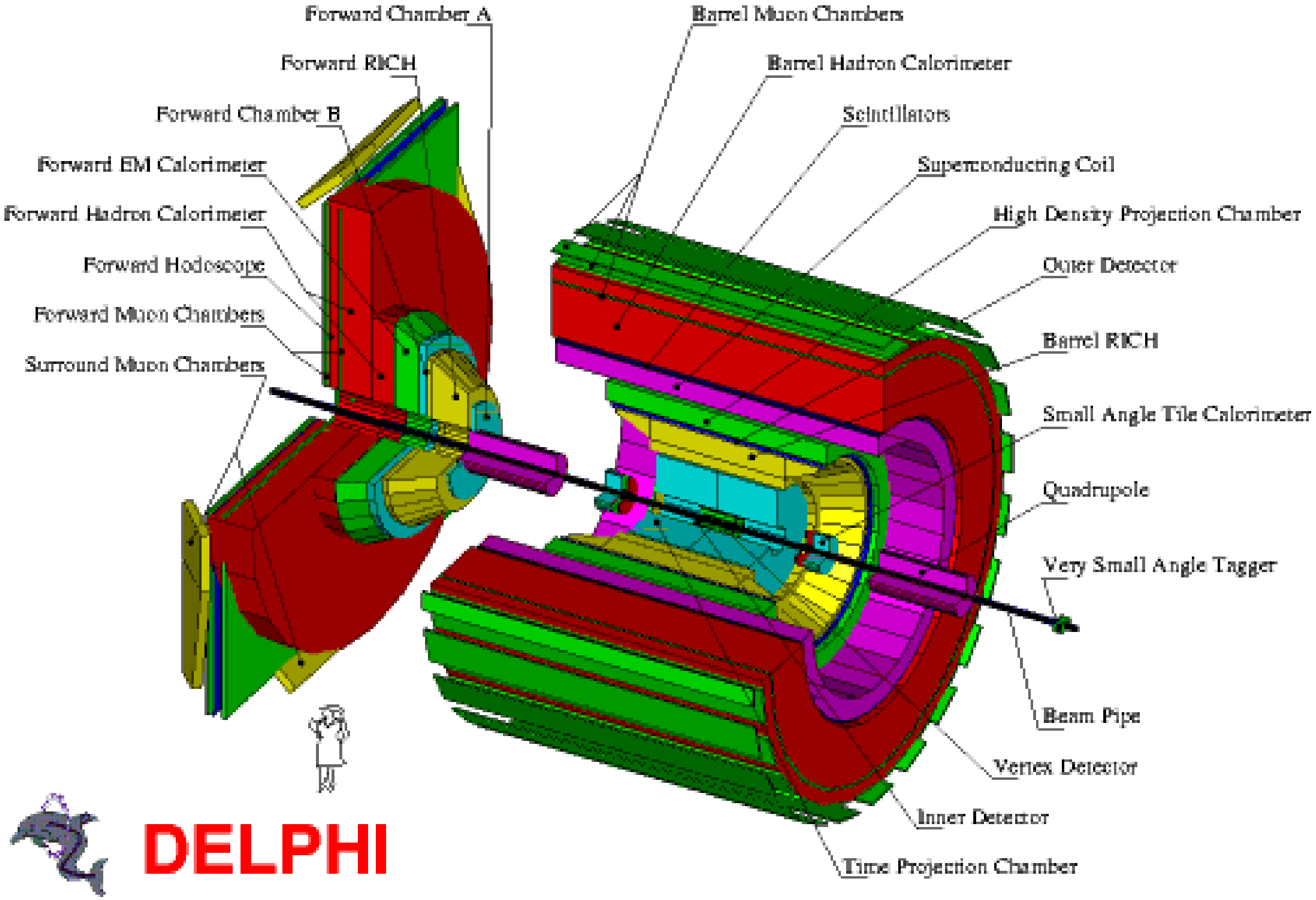


Figure 34: The DELPHI detector at LEP