# Particle detectors

## Eyes to see particles

October 12, 2021 and Sehwook Lee

# Contact


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- If you have any questions on particle detectors, don't hesitate to send me email.
- References

  - Calorimetry: Energy Measurement in Particle Physics (2nd Edition), Richard Wigmans, Oxford University Press
  - Calorimetry for Collider Physics, an Introduction, Richard Wigmans, Springer
  - Particle Physics Experiment at High Energy Colliders, John Hauptman, Wiley-VCH
  - Classical Electrodynamics, John David Jackson, Wiley
  - The Classical Theory of Fields, L.D. Landau
  - Classical Electromagnetic Radiation, M.A. Healed and J.B. Marion
  - Principles of Optics, Max Born

# Particle interaction with media

- This lecture will be offered in SPDAK 2022 (Jan. 17 ~ Jan. 21 in 2022)
- You will be able to join lectures via Zoom and Youtube

All text and figures in slides are from prof. Richard Wigmans' note for Nuclear and Particle Physics lectures offered at TTU in Spring 2013

# Ionization detectors

- Detect the electrons and ions liberated in the ionization processes along the path of the particle through the detector medium
- Electrically charged particles are collected at a charged electrode
- The electron-ion pairs do not recombine into neutral atoms before being collected
    - applying a sufficiently strong electric field across the medium
- Avoid that electrons be absorbed by other atoms on their way to the anode
    - use noble gases or liquids, which have no affinity for free electrons

# Wire chambers

## Ionization detectors

- Isolated wires: positive electrode of a high-voltage supply (anode)
- Housing of detector: grounded (cathode)
- A charged particle passing through the detector ionizes the gas atoms
- The electrons drift to the sense wire, and the ions will end up at the wall if the electric field between anode and cathode is strong enough
- In order to avoid recombination, the gas is chemically inert (noble gases (argon, xenon) dominate the mixture)

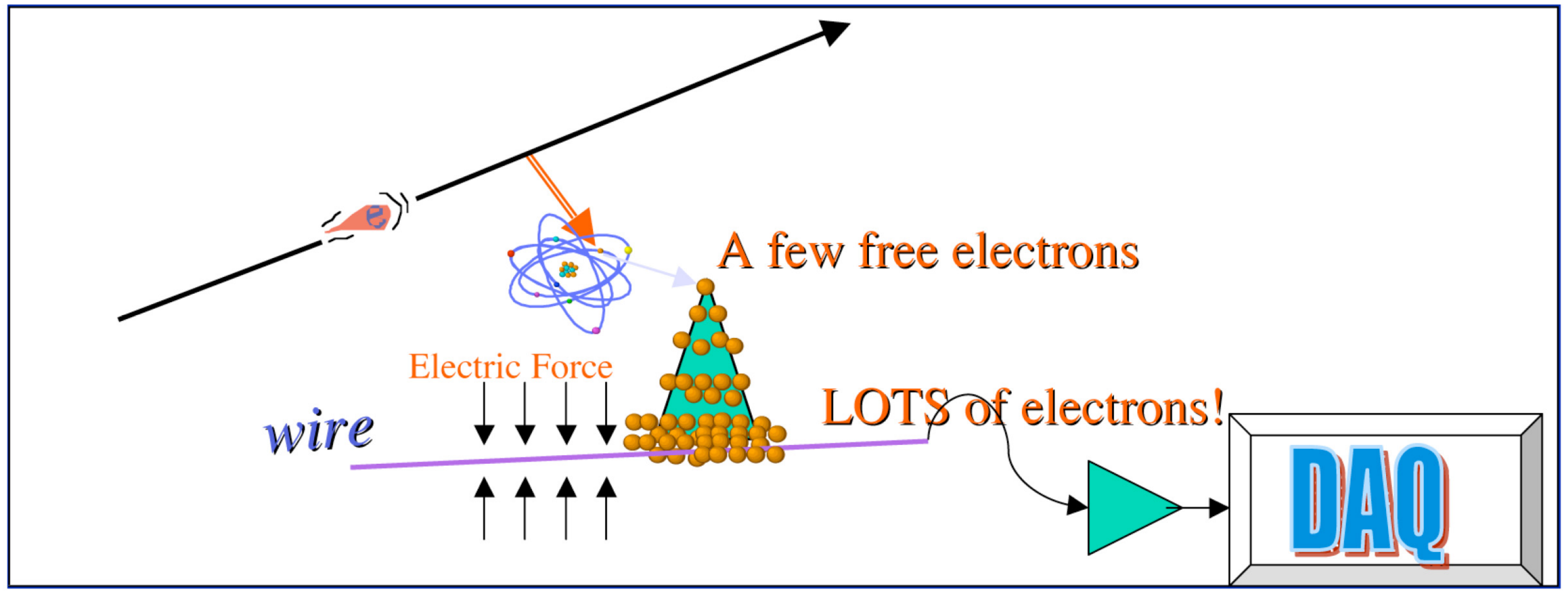



Figure 9.1: Operating principle of a detector based on collecting ionization charge.

# Wire chambers
## Ionization detectors

- When the charged particles arrive at the anode or cathode, the effect is equivalent to having an electric current run between the two electrodes
- The result will be a small voltage drop —> sensed by an amplifier
- The strength of the electric field increases tremendously at small r
- Close to the anode wire, the electrons are accelerated to the point
- They may ionize the gas medium
- These secondary electrons may in turn do the same
- Very close to the anode wire, there may be an important multiplication of charge carriers
- Avalanche formation

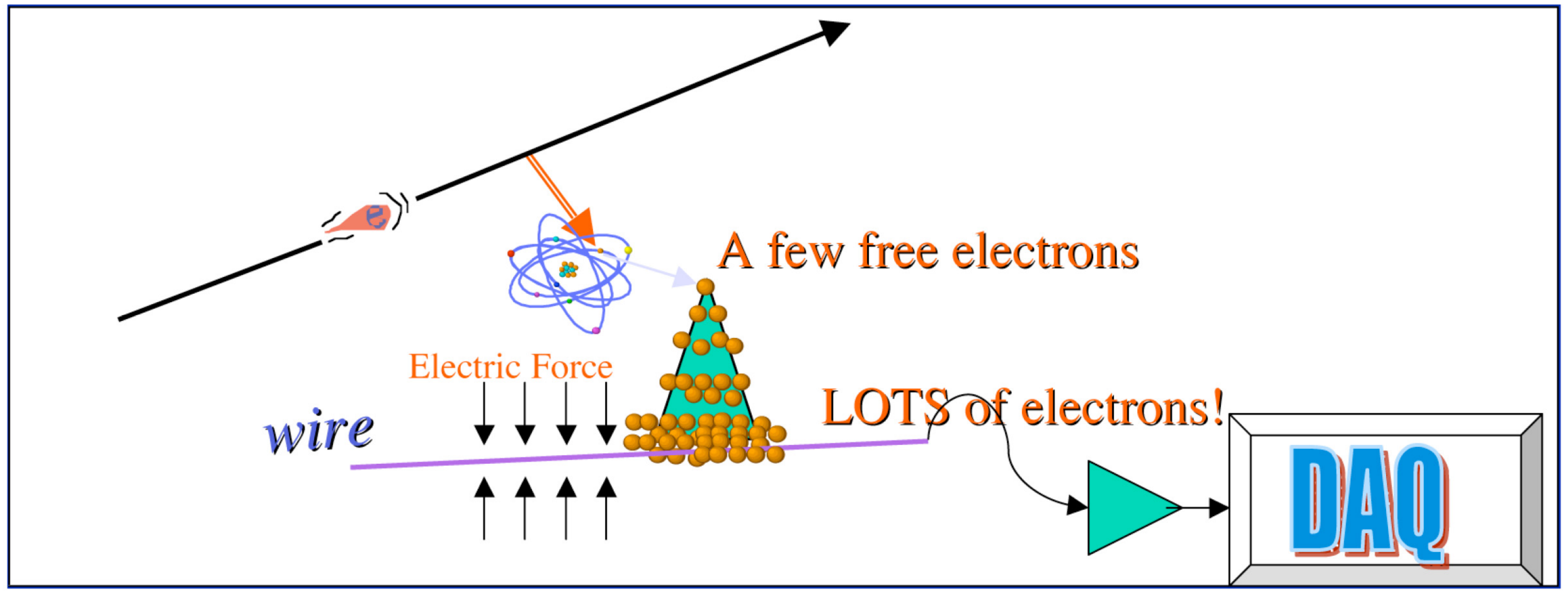



Figure 9.1: Operating principle of a detector based on collecting ionization charge.

$$V = k_C \frac{Q}{r} \quad \rightarrow \quad |\vec{E}| = \frac{\partial}{\partial r} V \quad \propto \frac{1}{r^2}$$

The electrostatic potential created by a charge Q at a distance r and the strength of the resulting electric field

# Wire chambers

## Ionization detectors

- At a very low voltage, the electrons and ions can recombine, the charge collection is incomplete
- As the voltage increases, recombination stops, the electric field is not yet strong enough for amplification of the collected charge. Detectors like this are operation in the ionization chamber mode. All ionization detectors based on liquid or solid media fall in this category
- As the strength of the electric field increases further (ΔV > 200 V), electrons are accelerated to the point where they can ionize other atoms. Charge multiplication factor is constant. Proportional regime. The measured signal is strictly proportional to the initial charge produced by the particle that traversed the detector.
- Beyond ~700 V, avalanche formation starts to occur. At higher voltage, this leads to a voltage breakdown (discharge) between the electrodes. There is no more proportionality. The detector turns into a digital device, which produces a discharge for every passing particle. Geiger-Muller counter.

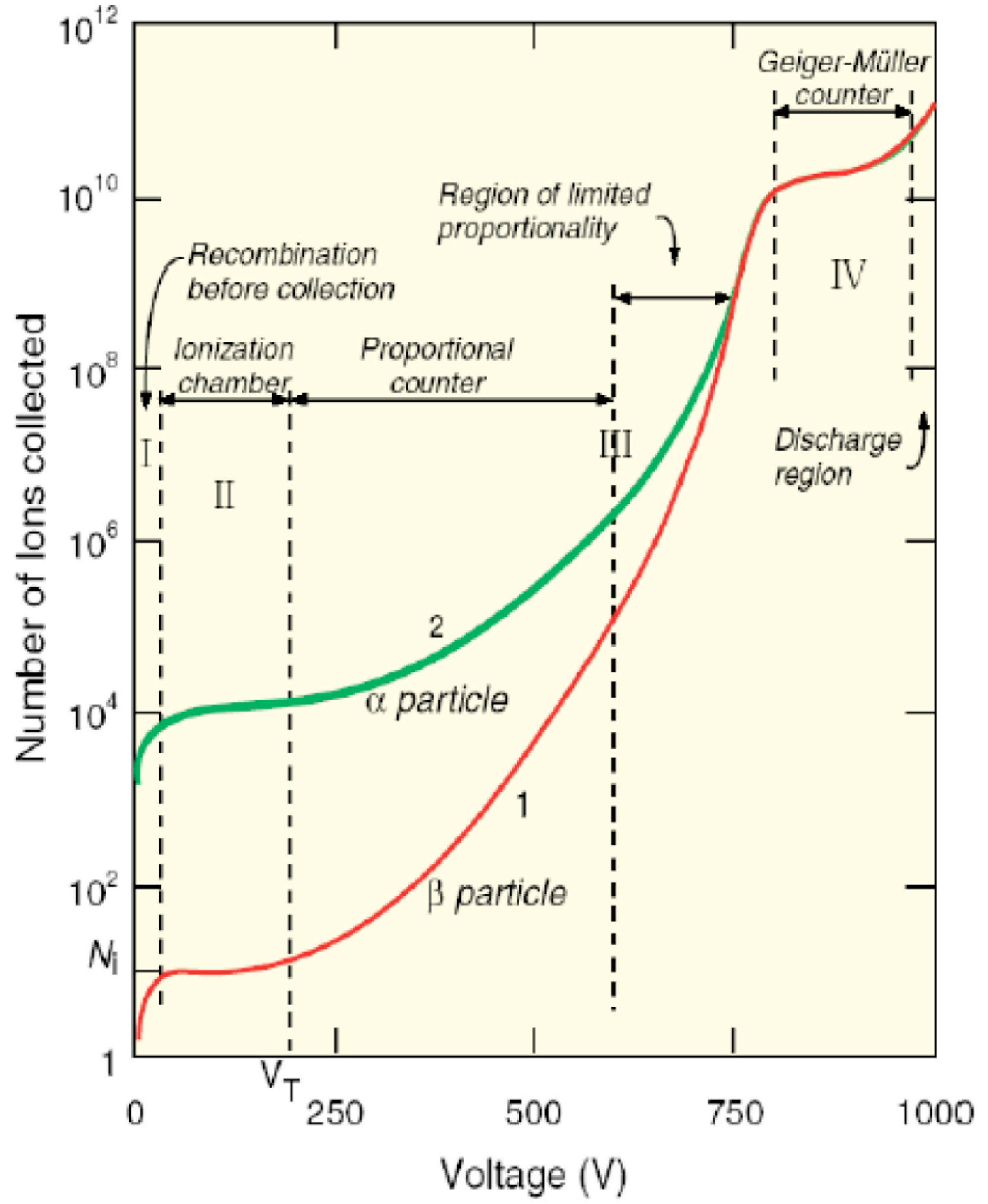



Figure 9.2: The different regimes in which wire chambers operate depend on the high-voltage applied between anode and cathode.

# Ionization chambers

- Operate at low voltage
- Produce very small signal
- Electronic noise is very important issue, so require ultra-low-noise electronics to proceed signals
- The absence of internal charge amplification, and the possible errors introduced by this, is an advantage for high precision measurement, which require very stable operation and a linear response
- For example, the measurement of the range of alpha particles
- The excellent stability and linearity in the ionization chamber mode can only be achieved if all electrons created in the ionization process reach the anode. Therefore, it is very important to keep electronegative impurities at an extremely low level.

# Proportional counters

- A particle creates ion/electron pairs along its path through the detector
- The electrons drift to the anode wire, in the vicinity of which the electric field becomes so strong that these electrons cause additional ionization of the gas
- Because of the larger signals, electronic noise is much less of a problem than in ionization chambers
- The anode wires have to be extremely thin, typical diameters between 10 and 50 μm in order to profit of the internal charge amplification
- Almost every experiment in particle physics uses them for tracking purposes
- Fig. 9.4: Multiwire Proportional Chamber (MWPC), invented by 1992 Nobel laureate Georges Charpak

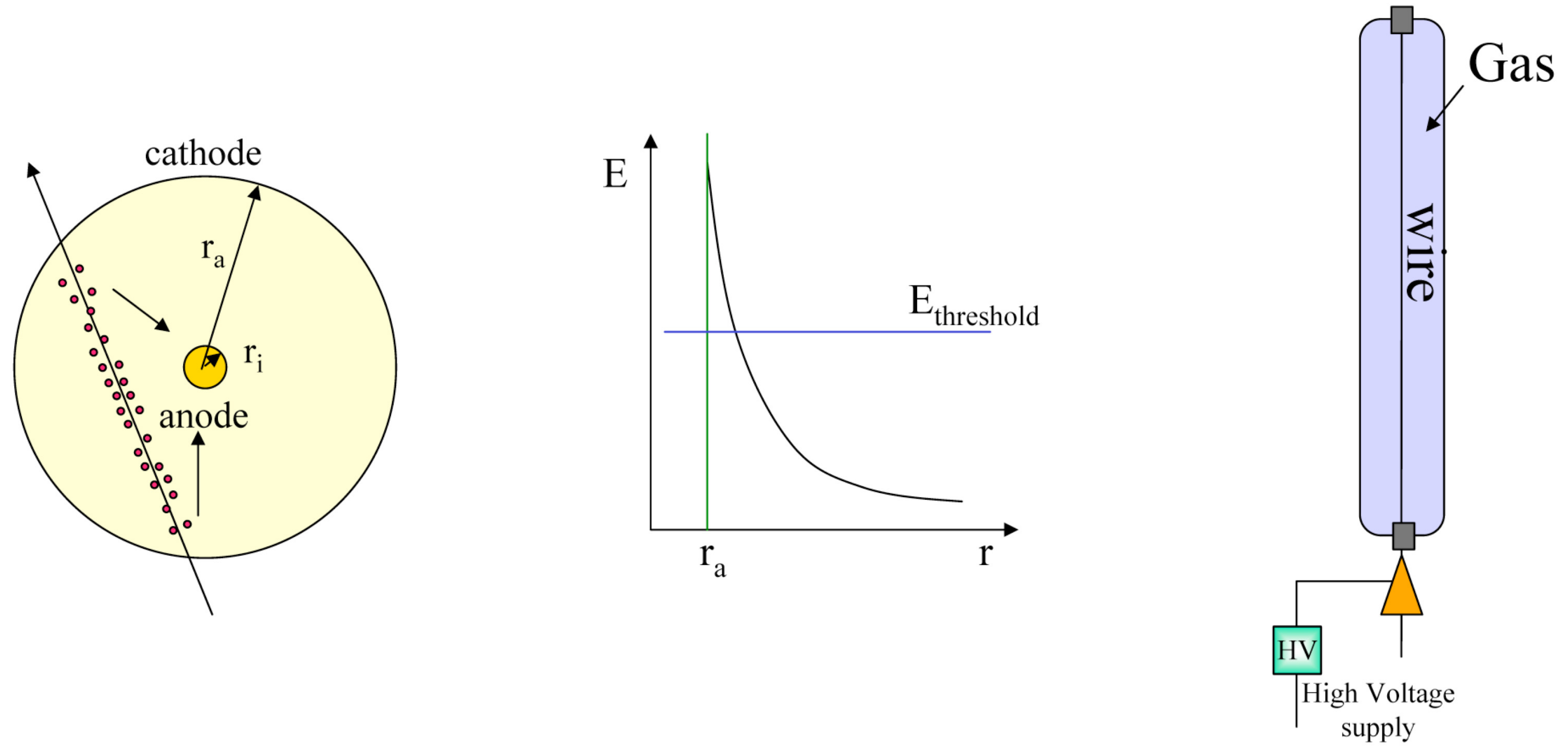



Figure 9.3: Operating principle of a proportional counter.

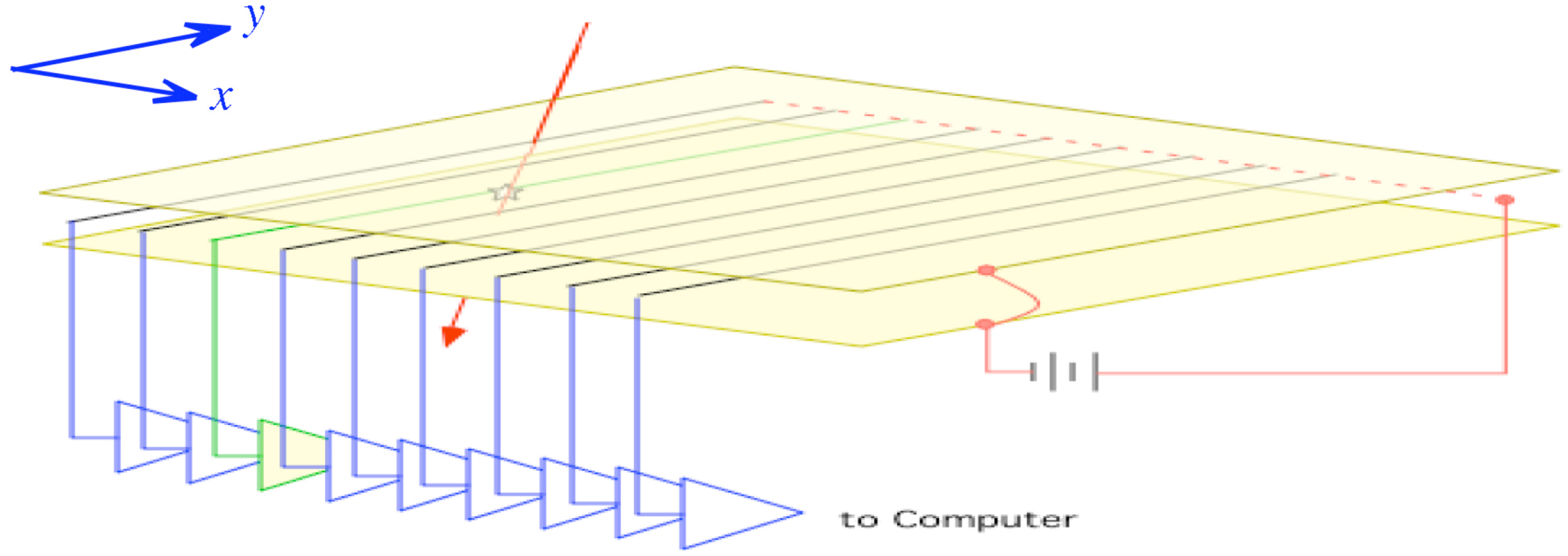



Figure 9.4: A multi-wire proportional chamber.

# Drift chambers

- Additional field wires with the purpose to make the strength of the electric field constant over a large area
- The electrons produced in the ionization processes may drift at a constant velocity over long distances (up to 1 m or so) to the anode
- Close to the anode, charge multiplication takes place
- If the drift velocity is constant, the position of the passing particle that caused the ionization can be inferred from the time
- The typical drift velocity in this type of detector is ~ 50 km/s, i.e. 50 μm/ns

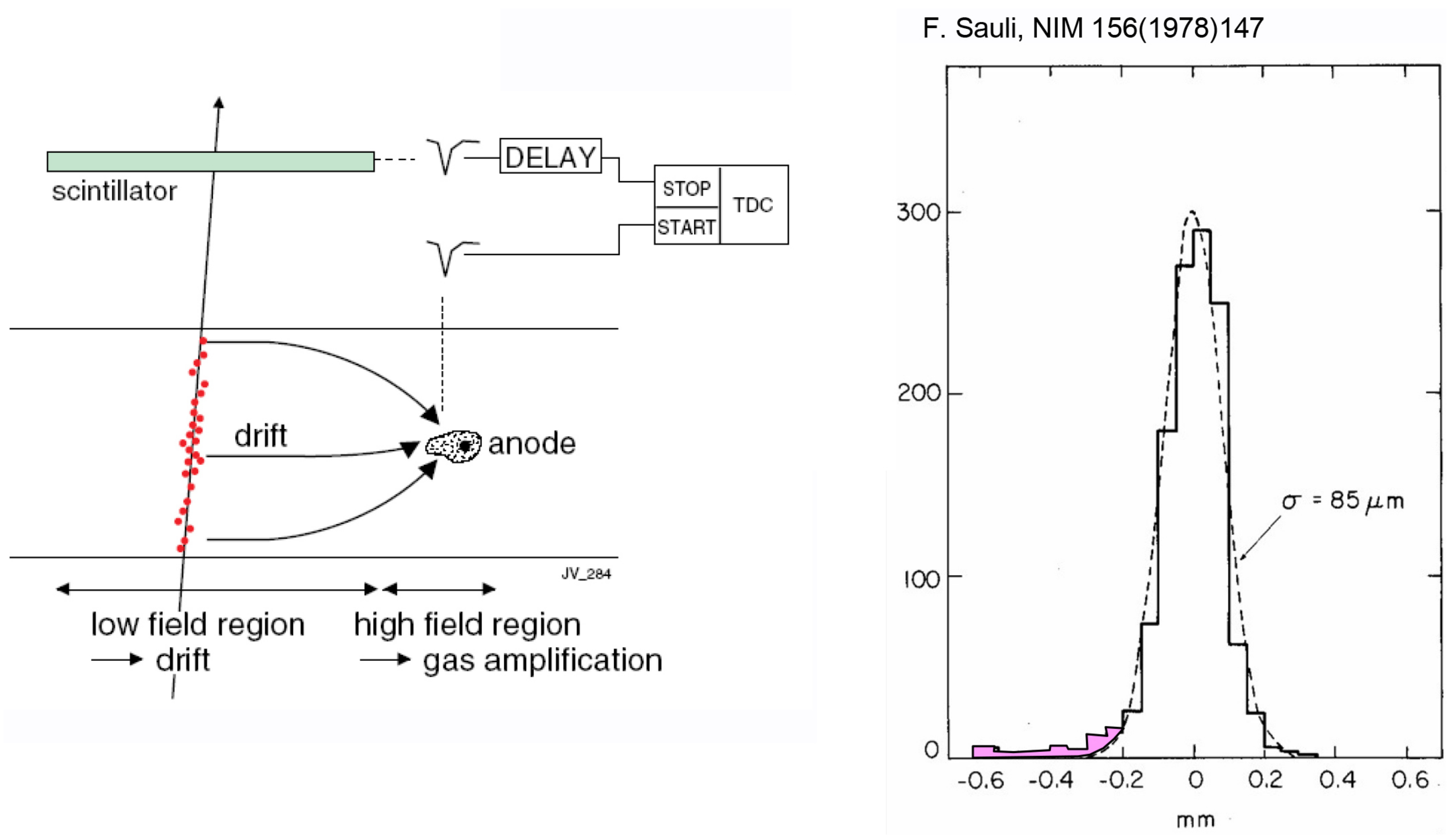



Figure 9.5: Operating principle of a drift chamber and position resolution achieved with this device.

Figure 9.6: The central tracking detector of the CDF experiment at Fermilab's Tevatron..

# Time Projection Chamber

- Many of wires are eliminated
- Tracks are reconstructed in three dimensions
- This type of detector uses a very high voltage to create the electric field in which the electrons drift towards the anode wire, 100 kV
- ALICE at CERN, STAR at Brookhaven
- A gas-filled cylindrical chamber with multi-wire proportional chamber at endplates
- The chamber is divided into halves by means of a central high-voltage electrode disc, which establishes an electric field between the center and the end plates
- z-coordinate is determined by measuring the drift time from the ionization event to the MWPCs located at the end plates.
- The MWPCs at the end are arranged with the anode wires in the azimuthal direction, which provides information on the radial coordinate, r

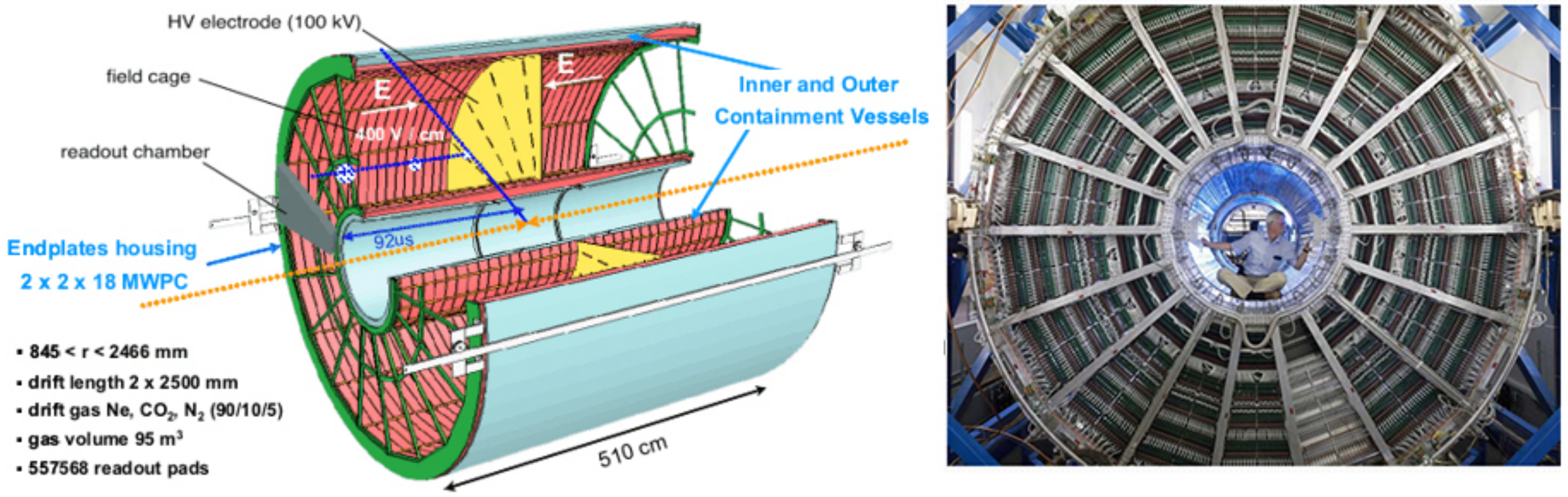



Figure 9.7: The Time Projection Chamber of the ALICE experiment at CERN's Large Hadron Collider.

# Non-wire ionization detectors

- Micromega
- The electrons produced by a charged particle passing the ionization region (a) drift towards the anode, which is a micromesh (c) in the holes of which the electric field strength is very high (b), so that charge amplification occurs
- The electrons are collected on patterned readout board
- (d) shows the type of position resolution

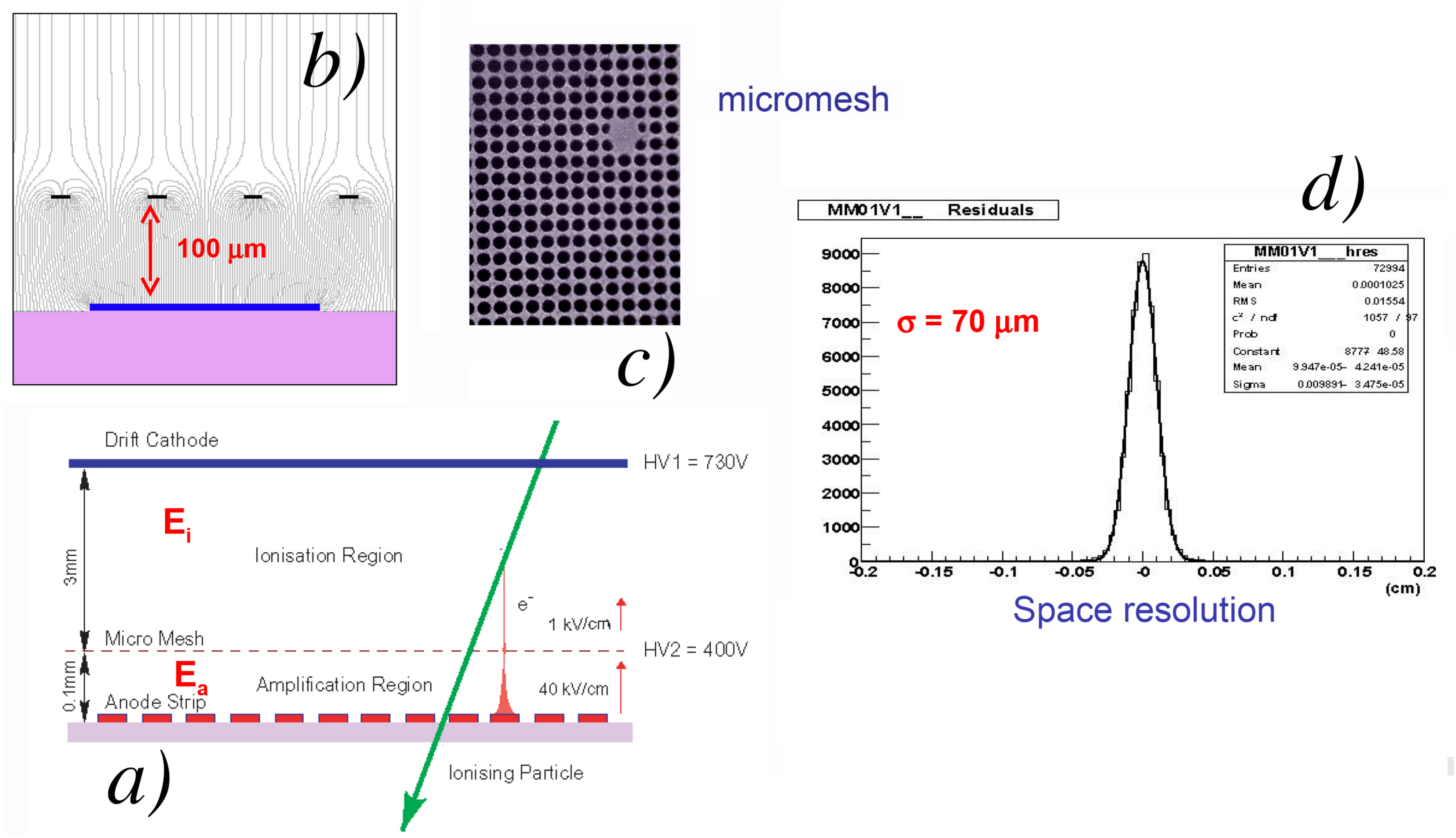



Figure 9.8: Operating principle of a micromega detector ($a$), the pattern of electric field lines ($b$), the fine mesh that separates the drift and amplification regions ($c$) and the typical position resolution obtained with such detectors ($d$).

# Geiger counters

- There is no relationship between the ionization charge created by the particle that traversed the detector and the resulting signal, since the avalanche development in the vicinity of the anode leads to a discharge for every ionization produced in the gas
- Typically, minimum ionizing particles lose 2 $MeV \cdot cm^2/g$ when passing through a medium
- Since gaseous media typically have a density of ~ 1 g/l, or $10^{-3}$ $g/cm^3$, mips loses 2 keV/cm —> produce typically 100 ionizations in this process since it takes about 20 eV to ionize an atom
- If there is no internal charge amplification in the detector, this event will lead to a pulse on the anode with and amplitude of the order of $10^{-8}$ V, since the capacitance C=Q/V between anode and cathode is typically of the order of 1 nF
- However, in an avalanche every electron can be multiplied by a factor $10^8$, which leads to pulses with an amplitude of several Volts
- Diagnostic purposes (e.g. investigate if a certain area is contaminated by radioactive material)

# Liquid argon

- Operates in the ionization chamber mode
- No internal charge multiplication
- A major advantage is the much larger density, which leads to correspondingly larger signals
- Two major technical challenges: (1) operation at cryogenic temperatures: 87 K (Ar), 120 K (Kr), 165 K (Xe) — boiling point —> requires a cryostat (dead material), (2) electronegative impurities have to be kept at very low levels (<< 1 ppm), to avoid electrons being captured by an atom on their way to the anode
- Active elements in several calorimeters (very compact construction, the liquid can be easily replaced (radiation damage is not as big a concern), e.g. ATLAS, D0 calorimeters
- Impractical to use these devices as tracking detectors

# Solid state detectors

- Semiconductor detectors: silicon, germanium, gallium arsenide
- The atoms are not ionized, the signals derive from the formation of electron-hole pairs
- The formation of such pairs requires only 2-3 eV in Si and Ge, vs ~ 30 eV for ionization of Ar, He
- These solid state detectors produce much larger signals than liquids
- A large number of charge carriers allows small (statistical) fluctuations and excellent resolutions
- For example, a 1 MeV energy deposit in a germanium detector produces 500,000 electron-hole pairs. The statistical fluctuations in this number ($\sqrt{n}$) amount to ~700. This energy can be measured with a resolution of only 0.14% (700/500,000). In other words, the 1 MeV energy deposit can be measured with a resolution of only 1.4 keV.

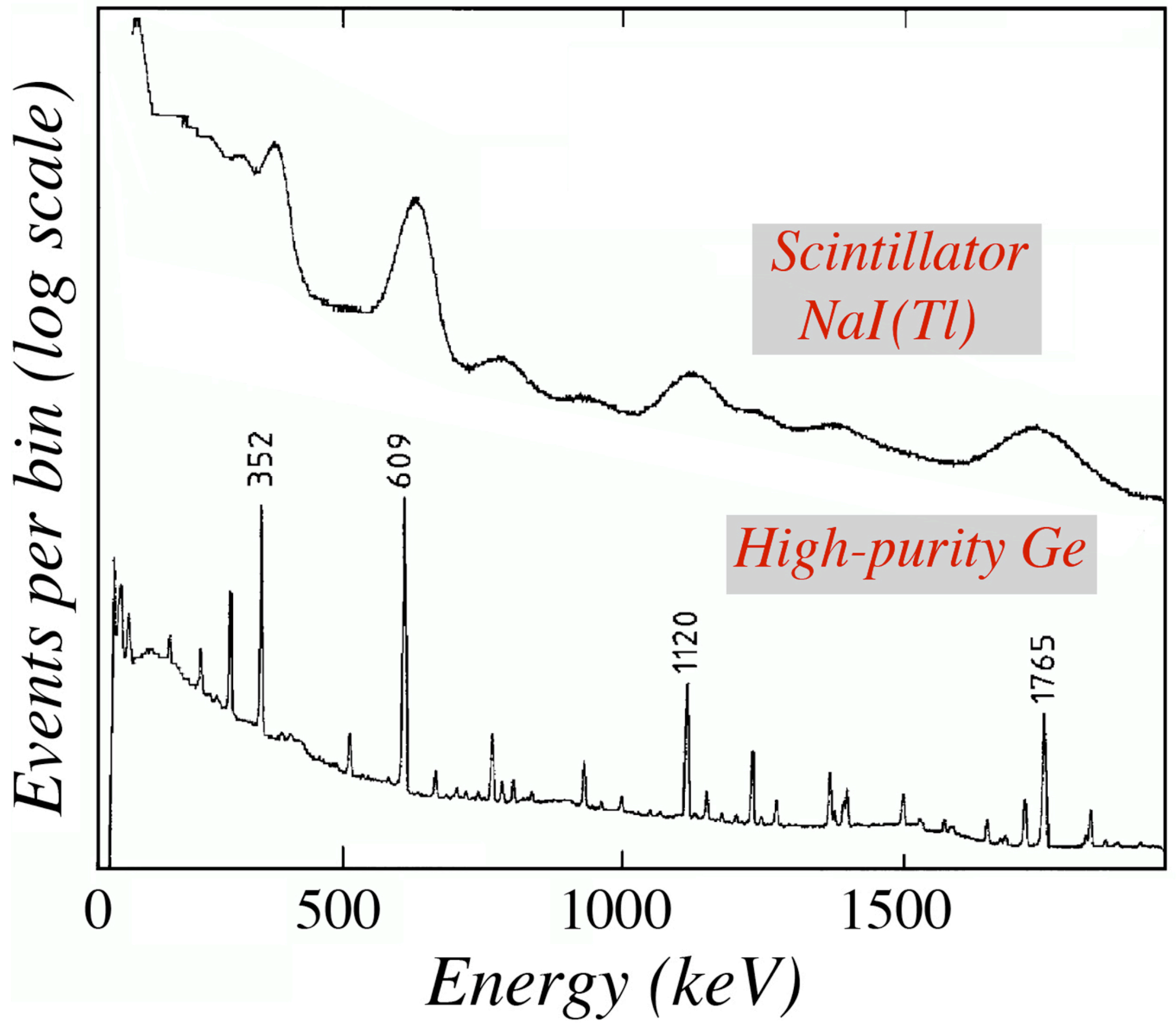



Figure 9.9: Spectrum of nuclear $\gamma$ rays emitted by natural uranium ore, measured with a (BGO) scintillation counter (*top*), and with a high-purity Germanium crystal (*bottom*)

# Solid state detectors

- The detectors of choice for high-precision tracking purposes
- Because the number of free charge carriers is so large, very thin (0.2-0.3 mm) wafers produce large enough signals, even for mip
- Electrically isolated strips or pixels on the surface of the wafer
- 20 μm strips are quite common
- It becomes possible to measure charged particle trajectories with accuracies of a few μm
- Detectors of this type are usually installed close to the point where colliding beams intersect
- Determine a primary vertex or the secondary vertex

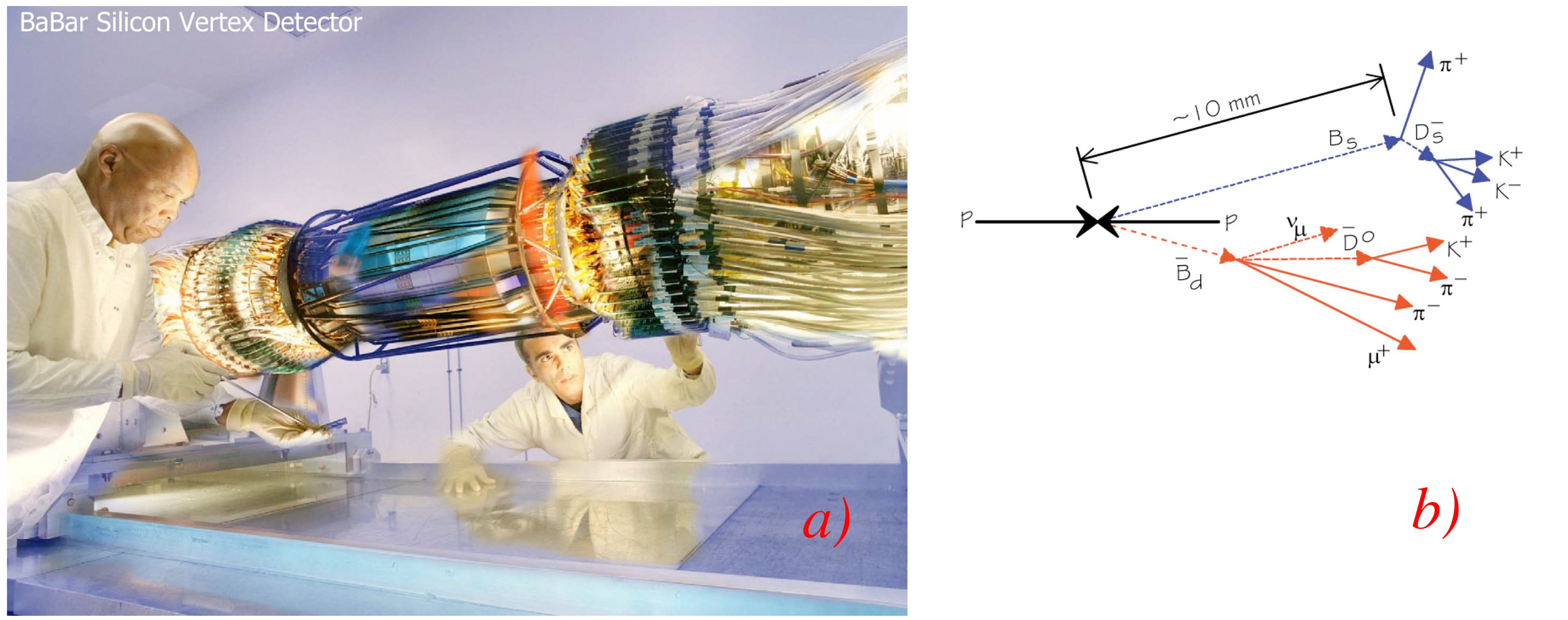



Figure 9.10: The Silicon Vertex Detector used in the BaBar experiment at SLAC. The insert shows the type of events that can be resolved with such instruments.

# Bubble chambers

- Invented while drinking beer by Donald Glaser in 1952 (Nobel laureate 1960)
- The workhorse of all particle physics experiments up to 1970
- The Big European Bubble Chamber, which contained more than 30 $m^3$ of liquid hydrogen or deuterium, took data until 1984
- A bubble chamber consists of a large cylinder filled with a liquid that is kept at a temperature slightly above its boiling point at atmospheric pressure
- The liquid is prevented from boiling by means of a piston which keeps it under pressure (압력밥솥과 같은 원리)
- As particles enter the chamber, the piston suddenly decrease its pressure, and the liquid enters into a superheated, metastable phase.
- Charged particles create an ionization track, around which the liquid vaporizes, forming microscopic bubbles. Bubble density around a track is proportional to a particle's energy loss
- Several cameras are mounted at various positions on the inside of the bubble chamber, allowing a three-dimensional image of an event to be captured
- The entire chamber is subject to a constant magnetic field

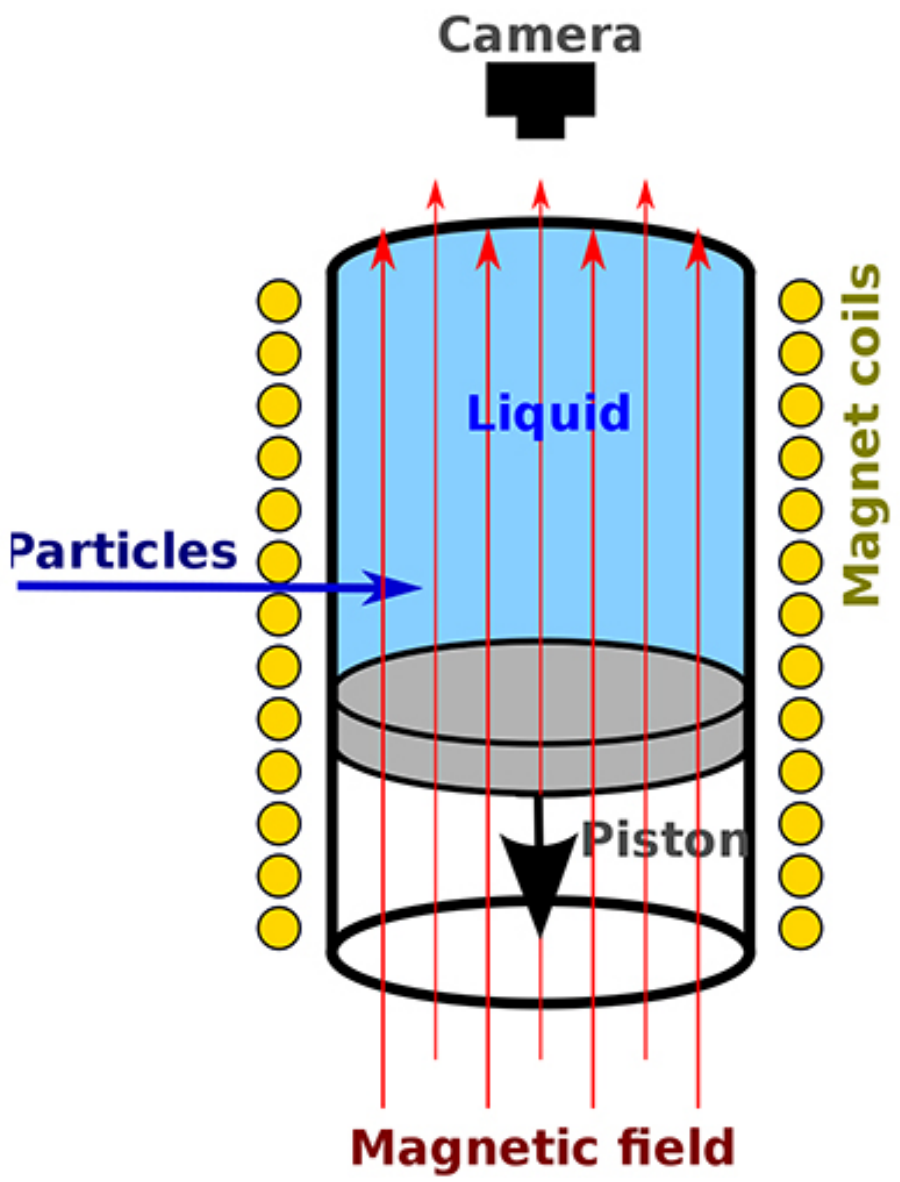



Figure 9.11: Schematic structure of a bubble chamber (*left* and BEBC, the Big European Bubble Chamber (*right*.

# Bubble chambers

- A beam of $K^-$ mesons enter the chamber from the bottom. Their momentum was so high that they barely got bent in the magnetic field
- Some of these kaons caused interactions in the liquid
- Fig. 9.12 (a): $\pi^+$ is produced that loses all its kinetic energy by ionizing the hydrogen, comes to a stop and decays into a μ+ (the little stub), which in turn decays into a positron. In the same event, a γ is produced, which itself is not visible since it is not charged. This γ gamma causes Compton scattering a few cm “northeast” of the interaction vertex and produces an electron.
- Fig. 9.12 (b): the production of a neutral kaon. This particle decays a few cm from the interaction vertex into a $\pi^+$ $\pi^-$

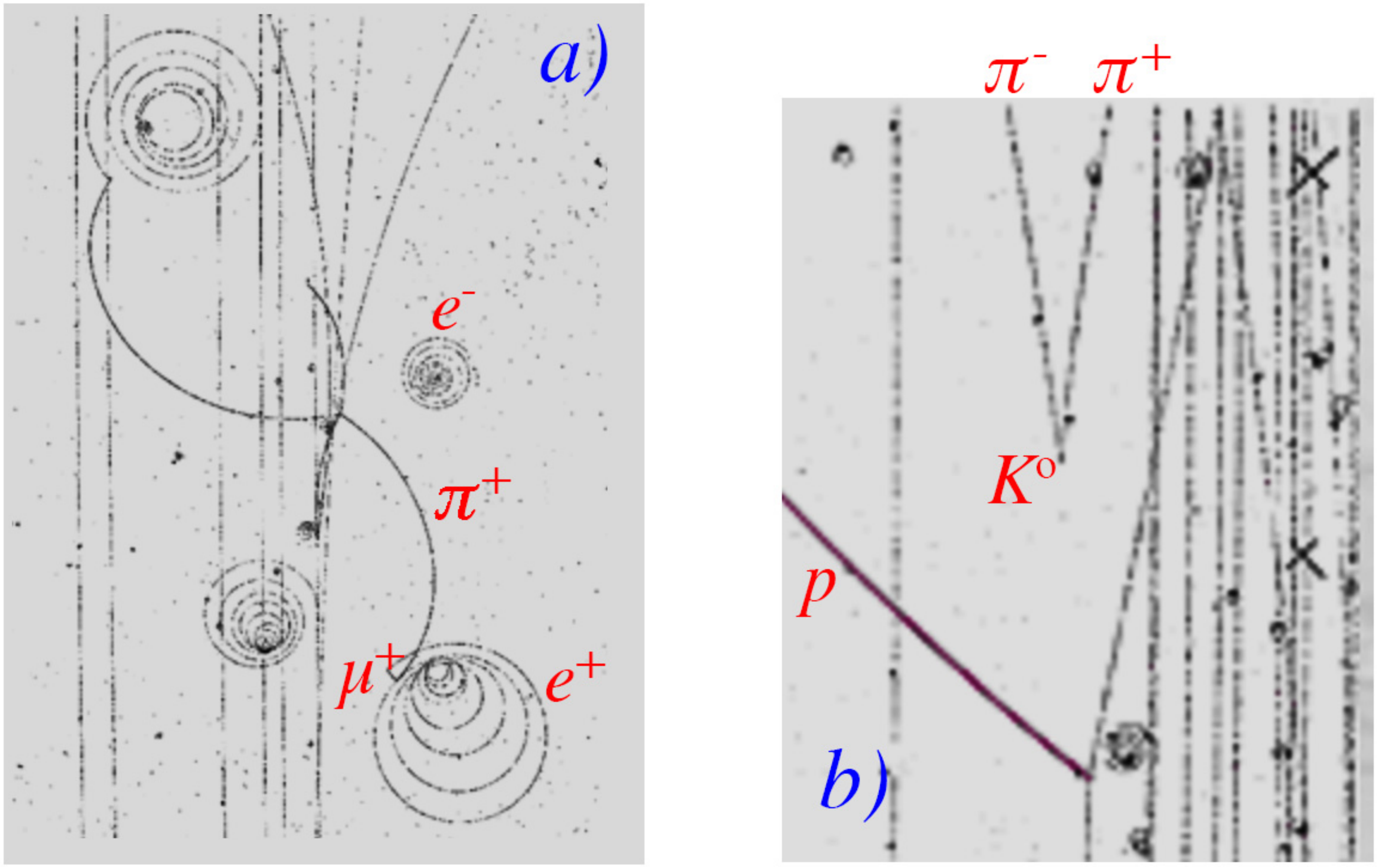



Figure 9.12: Examples of bubble chamber pictures in which noticeable events take place. The 2-meter hydrogen filled bubble chamber at CERN was exposed to a beam of $K^-$. In diagram $a$, the decay chain of a positive pion is visible ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$). Diagram $b$ shows the production of a neutral particle ($K^0$), that decays after a few cm into a $\pi^+\pi^-$ pair.

# Bubble chambers

- The main drawback: the analysis was extremely laborious. This is the main reason why the shift to electronic detectors took place in the 1970s.
- However,  the level of detail provided by bubble chamber pictures has never been matched since
- Bubble chamber have contributed major discoveries in particle physics
- Fig. 9.13: the discovery of the $\Omega^-$ baryon

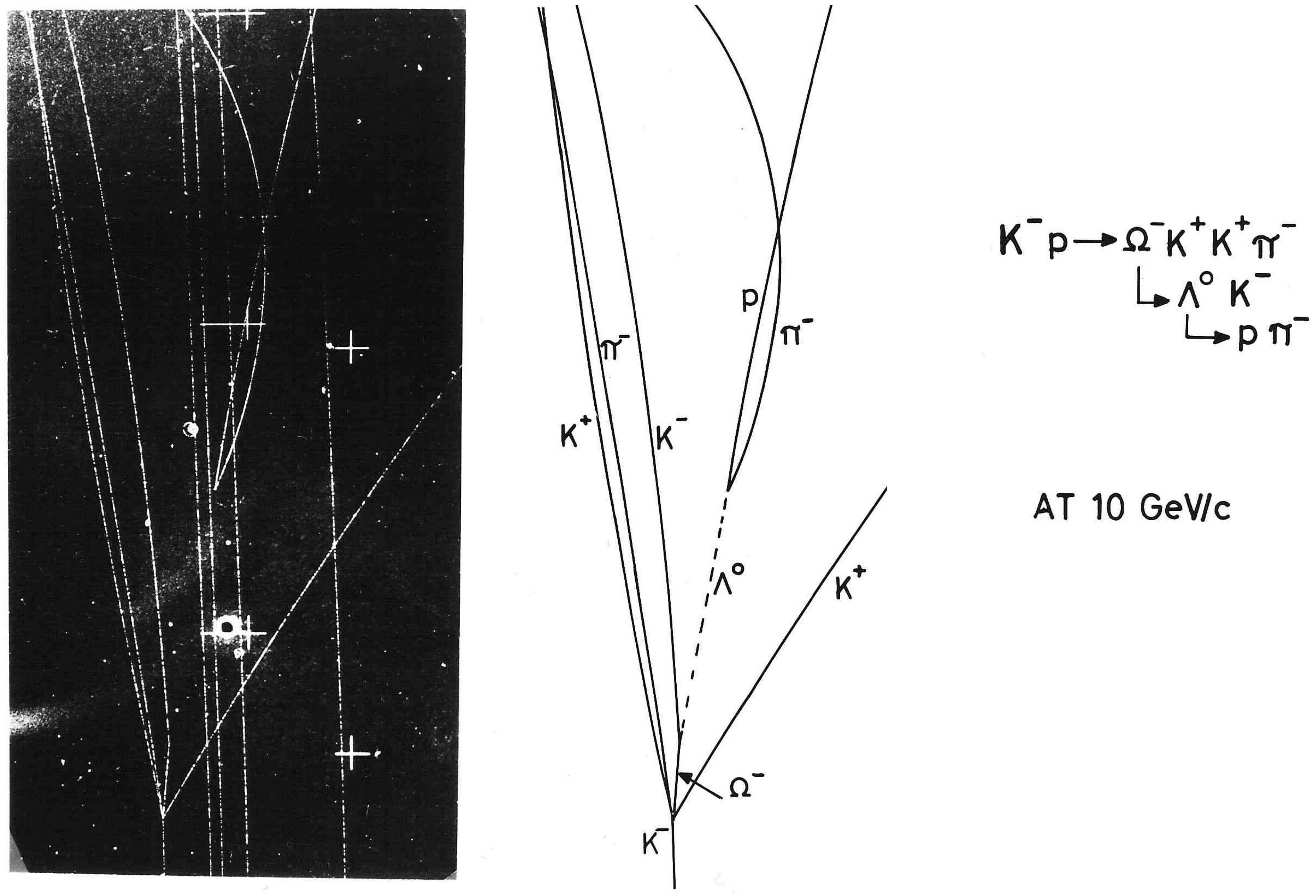



Figure 9.13: Example of a bubble chamber picture. This one shows a historically important event, namely the discovery of the $\Omega^-$ $(sss)$ baryon. The left side of the figure shows the actual picture, while the process that is taking place is reconstructed on the right hand side.

# Light detectors

- Apart from electric charge carriers produced in ionization or electron-hole formation, the other major source of information in subatomic physics experiments comes in the form of light
- This light is either produced in scintillation processes or the result of the Cerenkov effect
- In all cases, the detection is based on the photoelectric effect
- Detection of photons often involves alkali materials such as K, Na, Rb and Cs, since these have the smallest electronegativity, i.e. highest tendency to release electrons

# Scintillation light

## Light detectors

- Scintillation light is produce when certain molecules or atoms that are excited in the passage of a charged particle fall back to their ground state
- Two types of scintillating materials: organic and inorganic scintillators
- Organic scintillators: anthracene and naphthalene can be easily dissolved in plastic such as polystyrene and polymethylmetacrylate (PMMA)
    - efficient, fast scintillators with typical decay times of the order of 10 ns
    - They scintillate in the ultraviolet part of the optical spectrum (< 300 nm)
    - In order to avoid self-absorption, the plastic also has to be doped with a “fluor”(complex chemical compounds) that absorbs this UV light and re-emit it at longer wavelength (≳ 400 nm) —> such materials (POPOP, PMP, 3HF, p-terphenyl) are called wavelength shifters

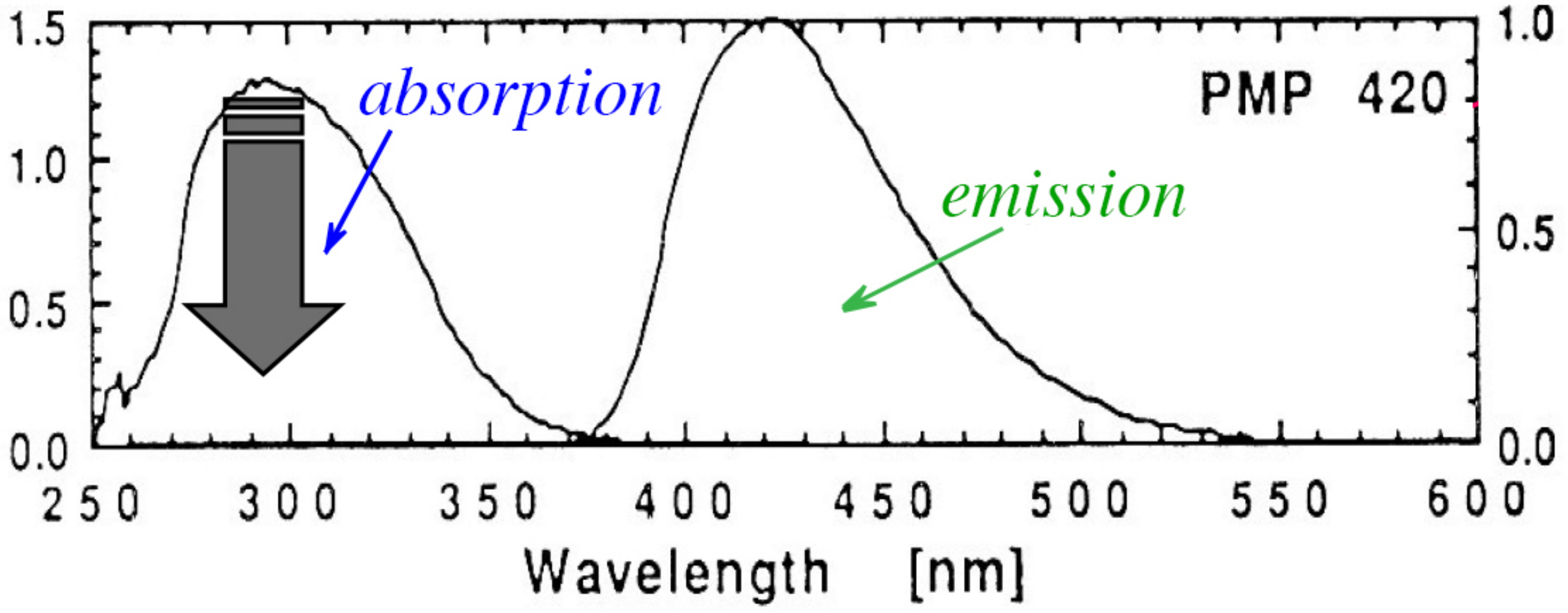



Figure 9.14: Absorption and emission spectra of a wavelength shifting fluor, PMP 420.

# Cerenkov light
## Light detectors

- Cerenkov light is emitted by particles traveling faster than the phase velocity of light in the detector medium, which depends on the index of refraction n ($v > c/n$)
- The light is emitted at a characteristic angle, $\theta_c = \arccos (\beta n)^{-1}$ with the particle direction
- Its intensity is proportional to $\sin^2\theta_c$ and the spectrum scales as $1/\lambda^2$
- KM3 experiment (a cubic kilometer of ice at the South Pole, detect Cerenkov light produced by extragalactic neutrinos), Auger experiment (detect air shower produced by extremely-high-energy cosmic ray in the atmosphere)
- Cerenkov threshold counter and Ring Imaging Cerenkov counters (identify particles based on their different velocities for a given momentum)
- Dual-readout calorimeter

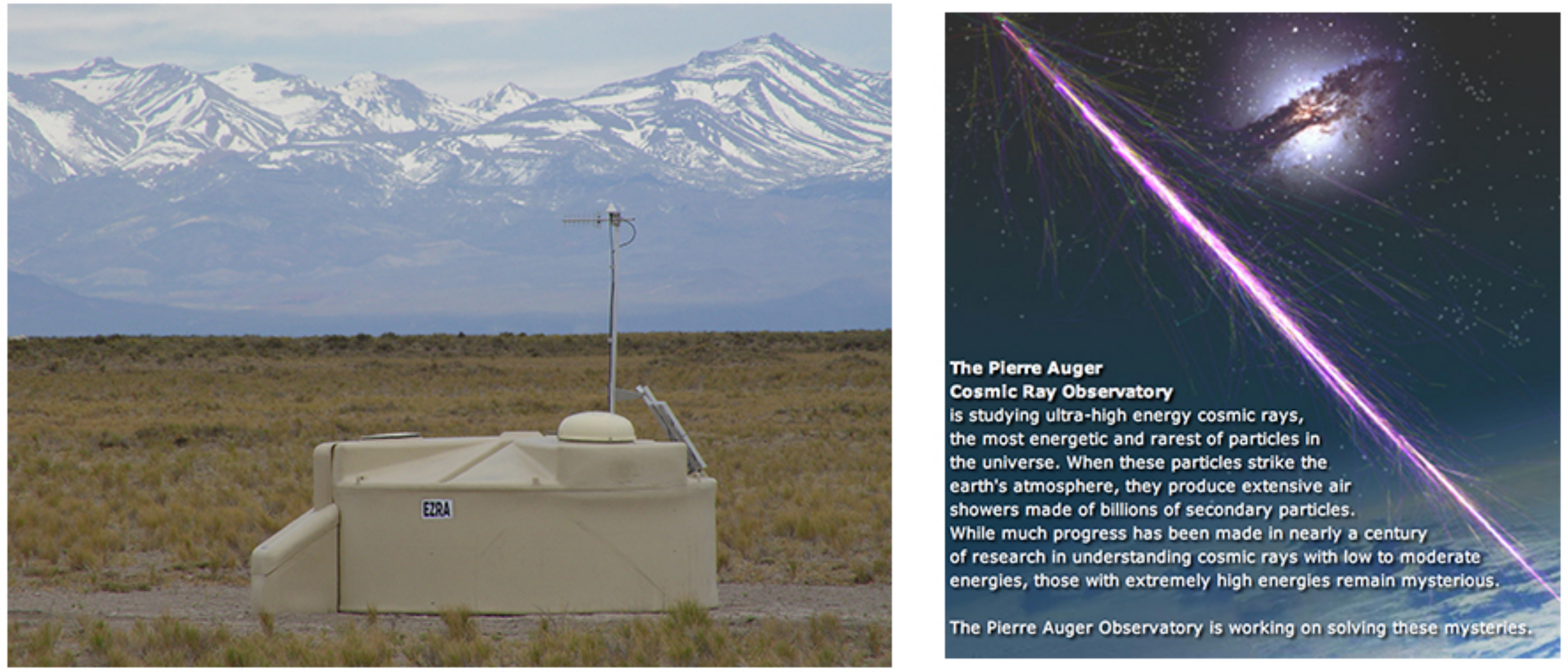



Figure 9.15: One of the more than 1600 detectors comprising the Auger experiment in Argentina, and the type of cosmic rays the experiment aims to detect.

# Conversion of light into electric pulses

## Light detectors

- Detectors of the light produced in scintillators or in the form of Cerenkov radiation convert the photons into photoelectrons
- Since the electron charge is very small, and the conversion efficiency (usually called the quantum efficiency) less than 100%, the electric signals need amplification

# Photomultiplier tubes (PMT)

# Light detectors

- **Photomultiplier tubes (PMTs)**, which may convert even single photons into a detectable electric pulse (Figure 9.16)
    - A PMT is a vacuum tube with a thin entry window, followed by a photocathode which is made of a material in which the valence electrons are weakly bound and which has a large cross section for the photoelectric effect.
    - Within the tube, there is a series ("stages") of electrodes (called dynodes) made of material with a low work function. These dynodes, of which there are typically 6-14 in commercially available PMTs, are operated at a gradually increasing electrostatic potential
    - Typical voltage differences between consecutive dynodes are 100-200 V
    - The dynodes accelerate the initial photoelectrons to the next stages, and multiply them through secondary emission at each dynode
    - The total gain, i.e. the combined total electron amplification factor, is typically somewhere between $10^4$ and $10^7$, depending on the number of dynodes and the high voltage applied
    - The quantum efficiency depends on the wavelength of the light, the photocathode material and the material and thickness of the entrance window
    - In typical PMTs, it peaks at ~ 25% for λ ~ 400 nm and decreases at longer wavelength

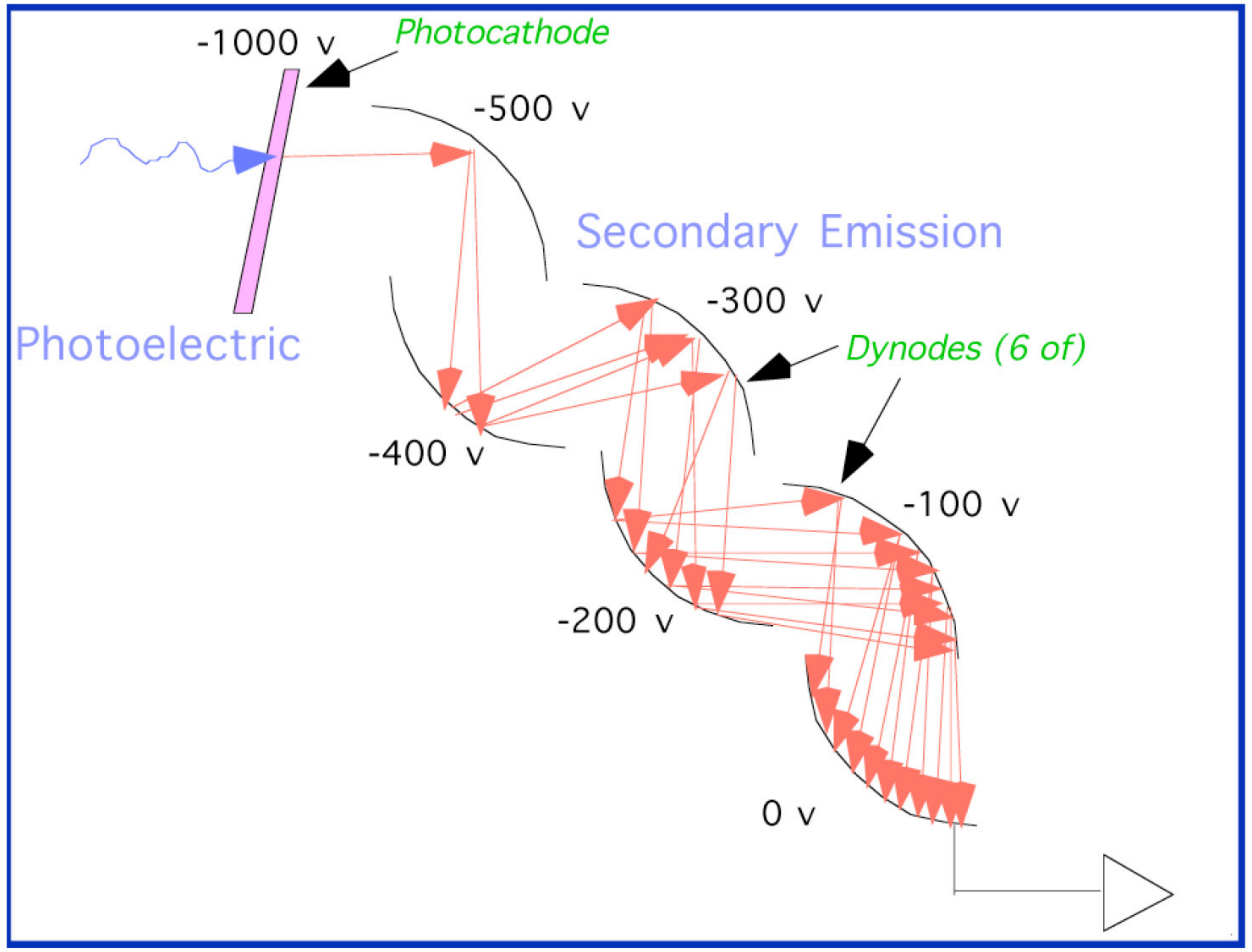



Figure 9.16: The operating principle of a photomultiplier tube (PMT).

# Solid state device

## Light detectors

- Solid state device, usually a semiconductor
- Absorbed photons are detected by internal photoelectric effect
- The absorbed photon imparts enough energy to an electron to lift it into the conduction band
- These electrons can then create a photocurrent
- Light detectors of this type include silicon photodiodes, avalanche photodiodes (APD) and pixelized avalanche photodiodes operating in the Geiger mode (SiPM)
- The advantages of this type of light detectors, compared to PMTs include
  - The ability to operate in a magnetic field
  - The larger quantum efficiency, especially at longer wavelengths, e.g. 80% for silicon at 600 nm, vs. < 5% for bialkali photocathodes
  - No need for highly stable high-voltage supplies

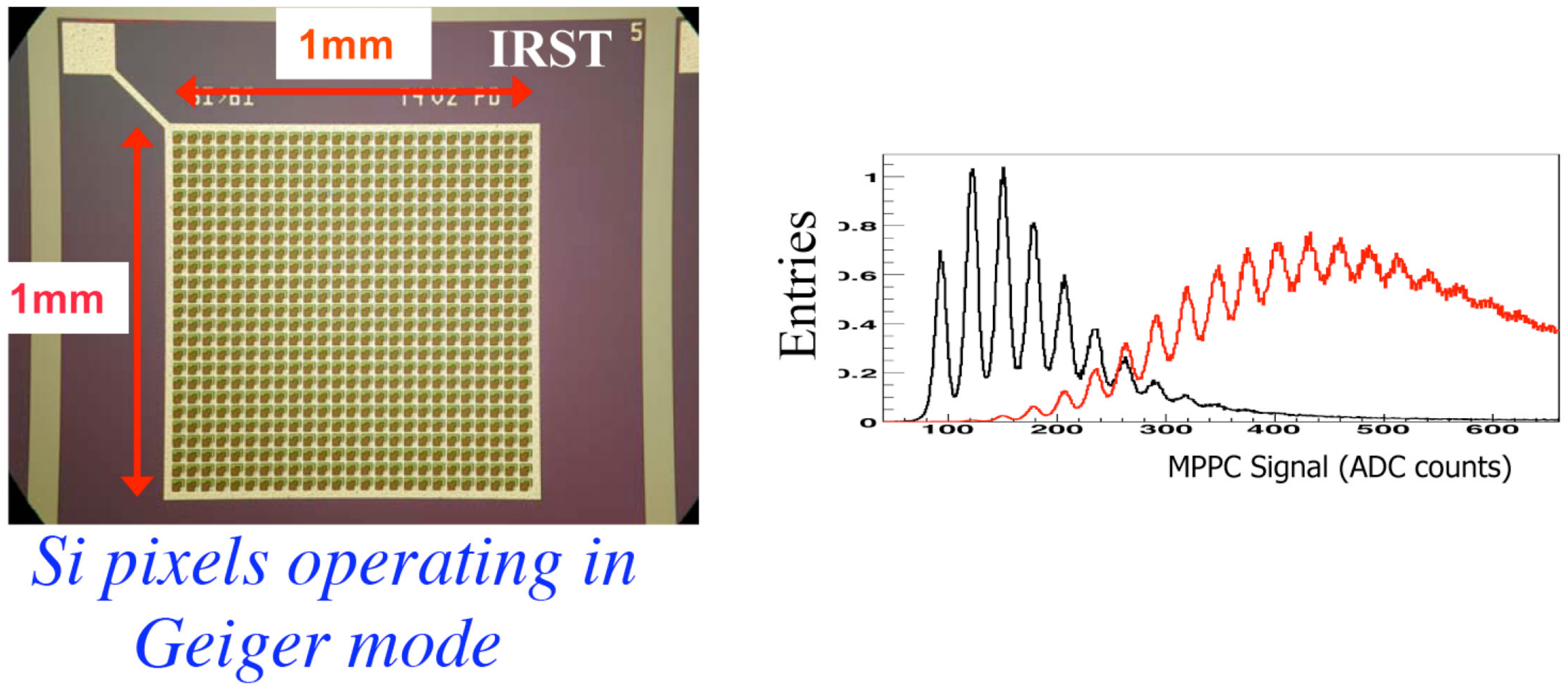



Figure 9.18: A silicon photomultiplier with 600 pixels/mm$^2$ (left), and some of the signal distributions generated by it.

# Calorimeters

- Calorimetric detectors are destructive
- There is usually nothing left to measure of a particle once the calorimeter is done with it, the only exception being muons.
- Calorimeters made of dense material can absorb even the highest energy manmade particles (TeV protons at CERN's LHC) in a relatively small volume

# Electromagnetic showers

## Calorimeters

- A high-energy γ enters an absorber, it converts (typically after 9/7 $X_0$ ) into an $e^+e^-$ pair.
- The electron and positron, which carry each approximately half of the photon energy, will lose that energy primarily through radiation, i.e. they emit new photons.
- These new photons convert in their turn into new $e^+e^-$ pairs, etc. (Figure 9.19).
- This particle multiplication continues until the point where the average energy of the shower particles has decreased to the point where γs will interact with the absorber through Compton scattering and photoelectric effect, and electrons and positrons will lose their energy through ionization rather than Bremsstrahlung.
- At this point, the shower maximum, the further multiplication of particles stops, and the remaining particles are gradually absorbed.
- The scale for this process is the radiation length.
- Typically, showers are completely absorbed in 25-30 $X_0$

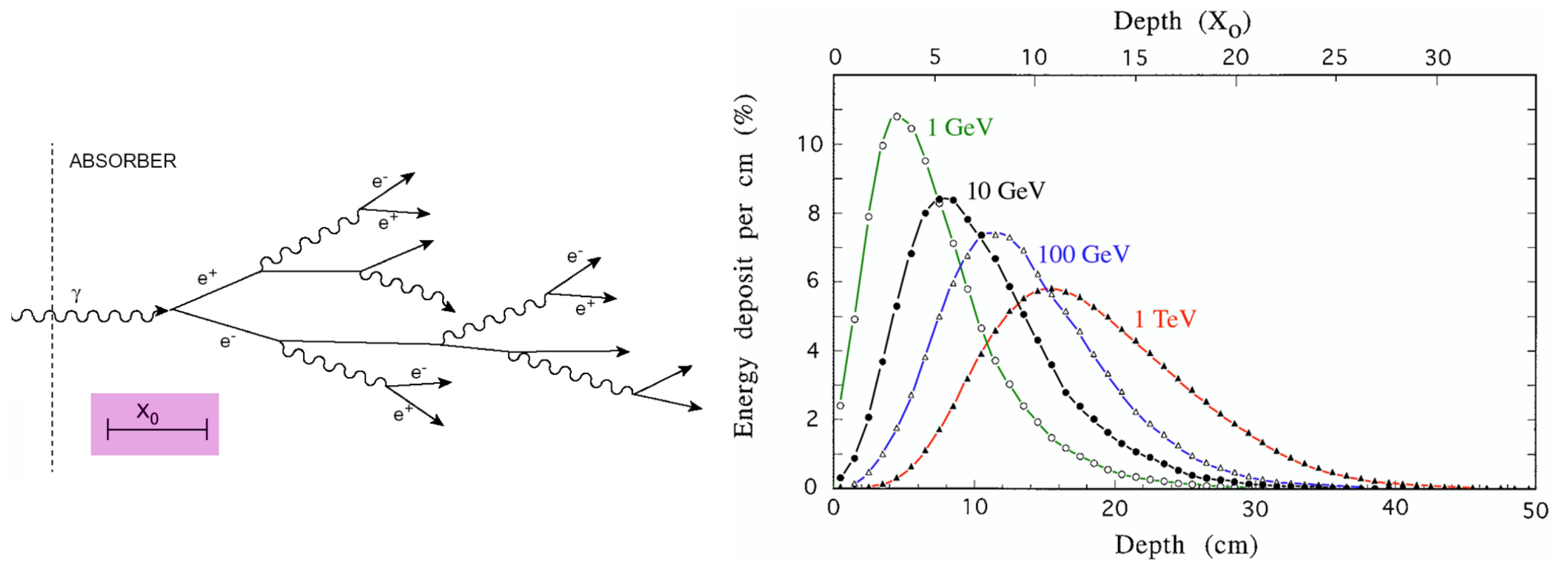


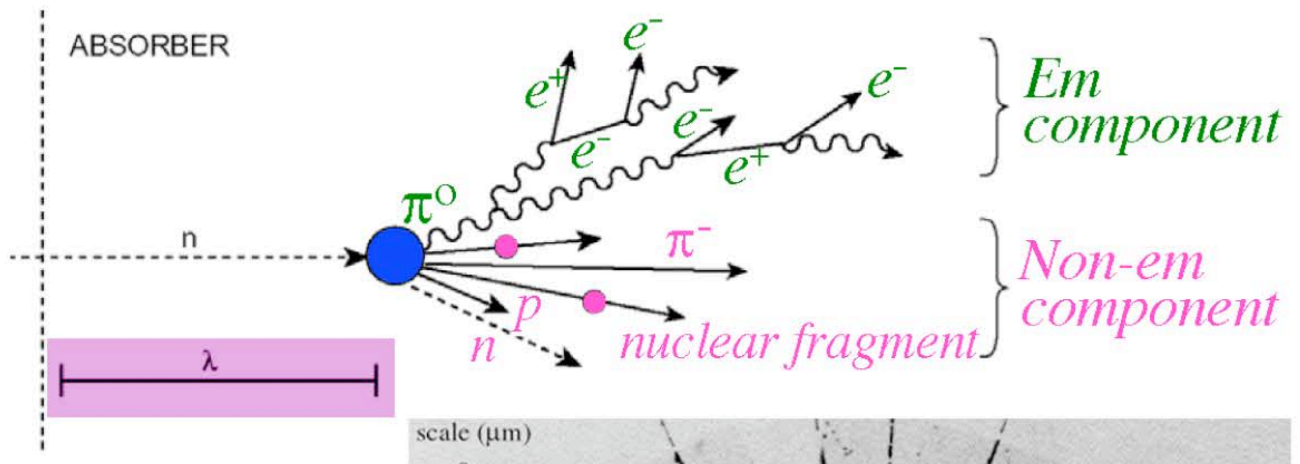

Figure 9.19: The early stages of electromagnetic shower development (*left*) and the deposited energy as a function of depth in a block of copper for electrons of different energies (*right*).

# Hadron showers

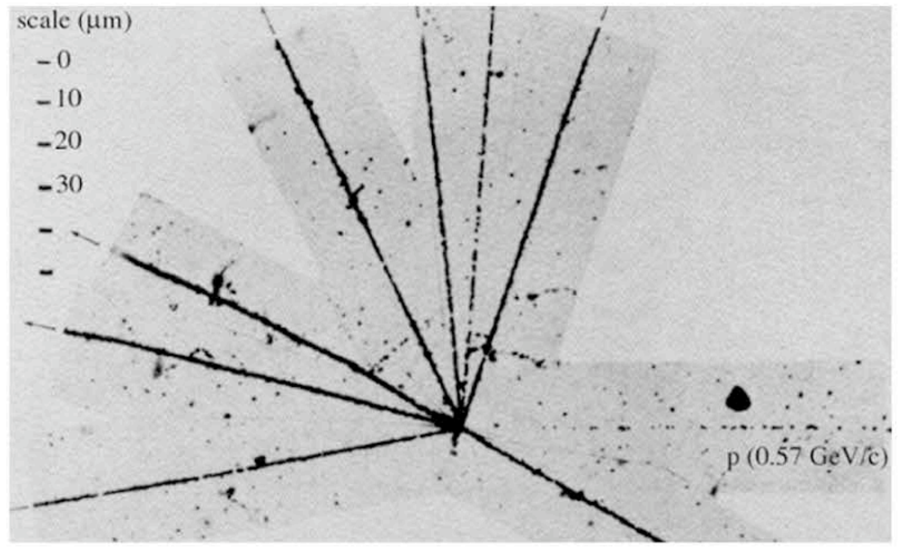
## Calorimeters

- Nuclear reactions play an important role
- The incoming proton or pion loses some energy by ionizing the detector medium until it encounters an atomic nucleus
- At that point, a nuclear interaction takes place, in which the energy of the incoming particle is distributed among a certain number of secondary particles, as well as the hit nucleus, which typically explodes.
- The secondary hadrons travel themselves, on average, one nuclear interaction length and repeat this process until the energy of the remaining particles is such that they simply range out, i.e. lose their remaining energy through ionization of the medium
- Unstable particles such as pions will decay, as illustrated in fig. 9.12
- The scale for this absorption process is the nuclear interaction length, $\lambda_{int}$
- Typical hadron calorimeters in accelerator experiments are 7-8 $\lambda_{int}$ deep, which is enough to contain even the highest energy LHC particles, on average, at the 95+% level.

- *A hadronic shower consists of two components*




- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 $\gamma$
- *Hadronic (non-em) component*
  - charged hadrons $\pi^\pm$,$K^\pm$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft $\gamma$'s (15%)
  - break-up of nuclei (*"invisible"*) (40%)



# Homogeneous Calorimeter

## Calorimeter

- The functions of absorber and detector are combined in the same material
- In accelerator experiments, such detectors are exclusively used to detect electromagnetic showers
- The energy resolution of such calorimeters is dominated by fluctuations in the number of detected photoelectrons
- Since the signal (measured in number of photoelectrons N) is proportional to the deposited energy, the standard deviation is $\sqrt{N}$
- Therefore, the relative energy resolution $\sigma(E)/E \propto E^{-1/2}$

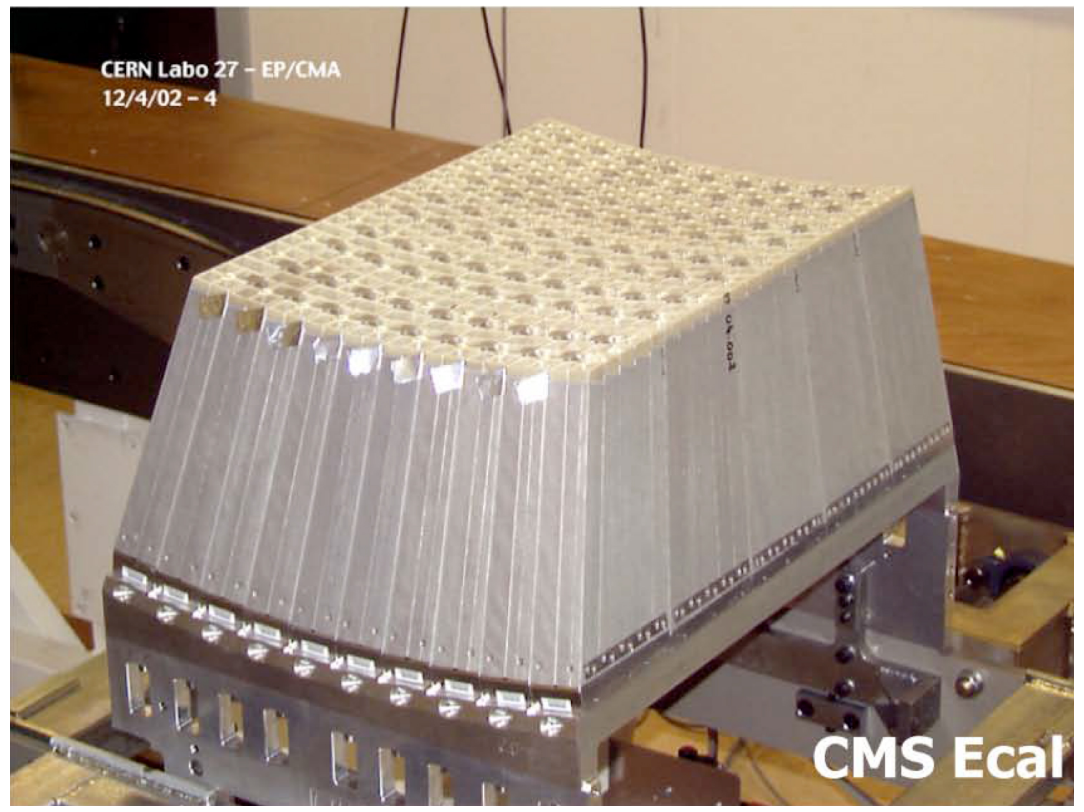



Figure 9.20: A module of the electromagnetic calorimeter of the CMS experiment at CERN's Large Hadron Collider. This detector consists of more than 60,000 $PbWO_4$ crystals.

# Sampling Calorimeter

## Calorimeter

- Only a small fraction of the deposited energy is deposited in the "active" detector component
- The energy resolution in such sampling calorimeters is typically considerably worse than in homogeneous ones
- Sampling calorimeters are especially used for detecting hadrons
- This is not only because that requires typically at least an order of magnitude more material than for electromagnetic showers, so that more cost effective solutions are imperative, but also because hadron calorimetry suffers from intrinsic limitations to the possible energy resolution
- These limitations derive from the fact that the fraction of the hadron's energy that ends up in the form of a detectable signal exhibits rather large fluctuations because a certain amount of energy is needed to provide the nuclear binding energy of nucleons released in the nuclear interactions in the absorption process
- This binding energy does not contribute to the measurable signal
- This effect limits the energy resolution of even the very best hadron calorimeters to ~ 30%/√E, with the energy E measured in GeV

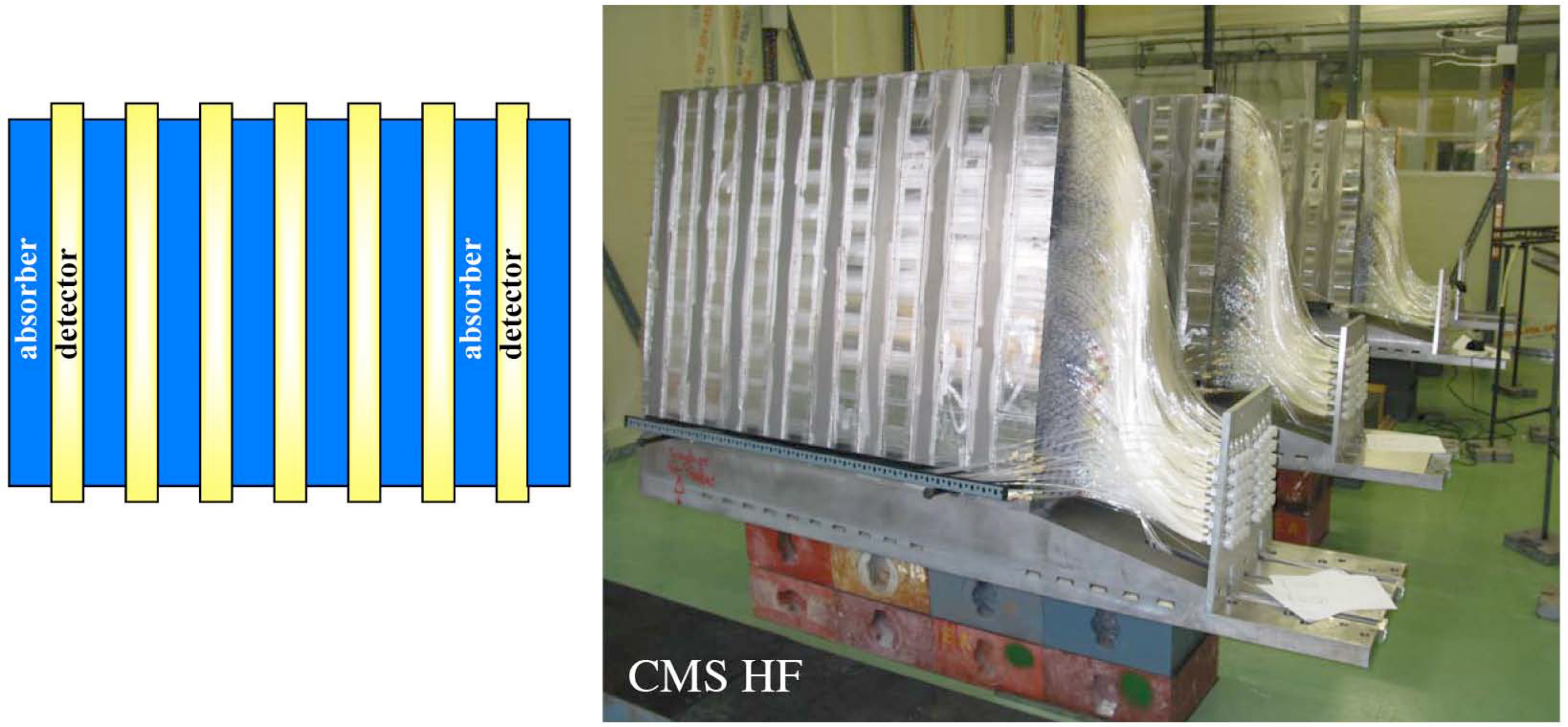



Figure 9.21: Schematic structure of a sampling calorimeter (*left*. Modules of the forward calorimeter of the CMS experiment (*right*).

# Momentum Measurement

- The momenta of charged particles can be measured from the curvature of their trajectory in a magnetic field, since the centripetal force keeping the particle in its circular orbit is provided by the Lorentz force (see Figure 9.22)
- If the particle moves perpendicular to the magnetic field, as in the figure, this means that the momentum p = qBρ, i.e. equal to the product of the particle's charge, the strength of the magnetic field and the bending radius
- The larger the momentum of the particle, the larger the bending radius, and therefore the smaller the sagitta (Δs), which measures the deviation from a straight line
- The maximum momentum that can be measured in a given experiment is determined by the strength of the magnetic field, the length over which the particle traverses this field, and the position resolution of the detectors that measure the particle's trajectory

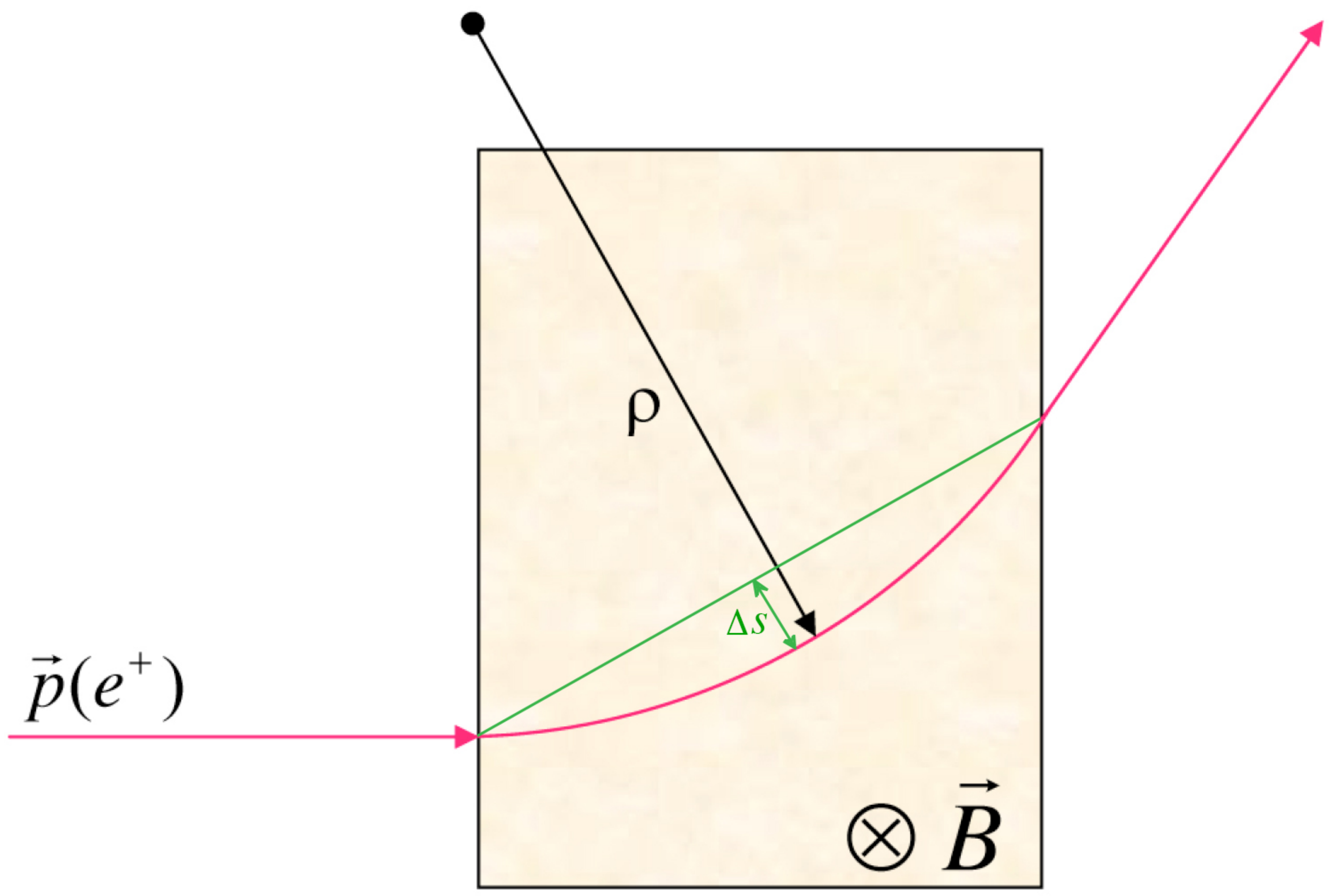



Figure 9.22: The effect of magnetic field on the trajectory of a charged particle).

$$F_L = q\,\vec{v} \times \vec{B} = F_c = \frac{mv^2}{\rho}$$

# Specific Ionization

## Particle identification

- The specific ionization, i.e. the energy loss per unit length in a medium traversed by the particle is an excellent way to identify non-relativistic particles
- For a given momentum, the velocity is inversely proportional to the mass for such particles, and therefore the velocity term ($1/\beta^2$) in the Bethe-Bloch formula leads to a large difference in $\langle dE/dx \rangle$ for particles of different mass
- This is illustrated in Figure 9.23, which shows that pions, kaons and protons with momenta in the range of 0.1 - 1 GeV/c can be easily distinguished on the basis of their specific ionization

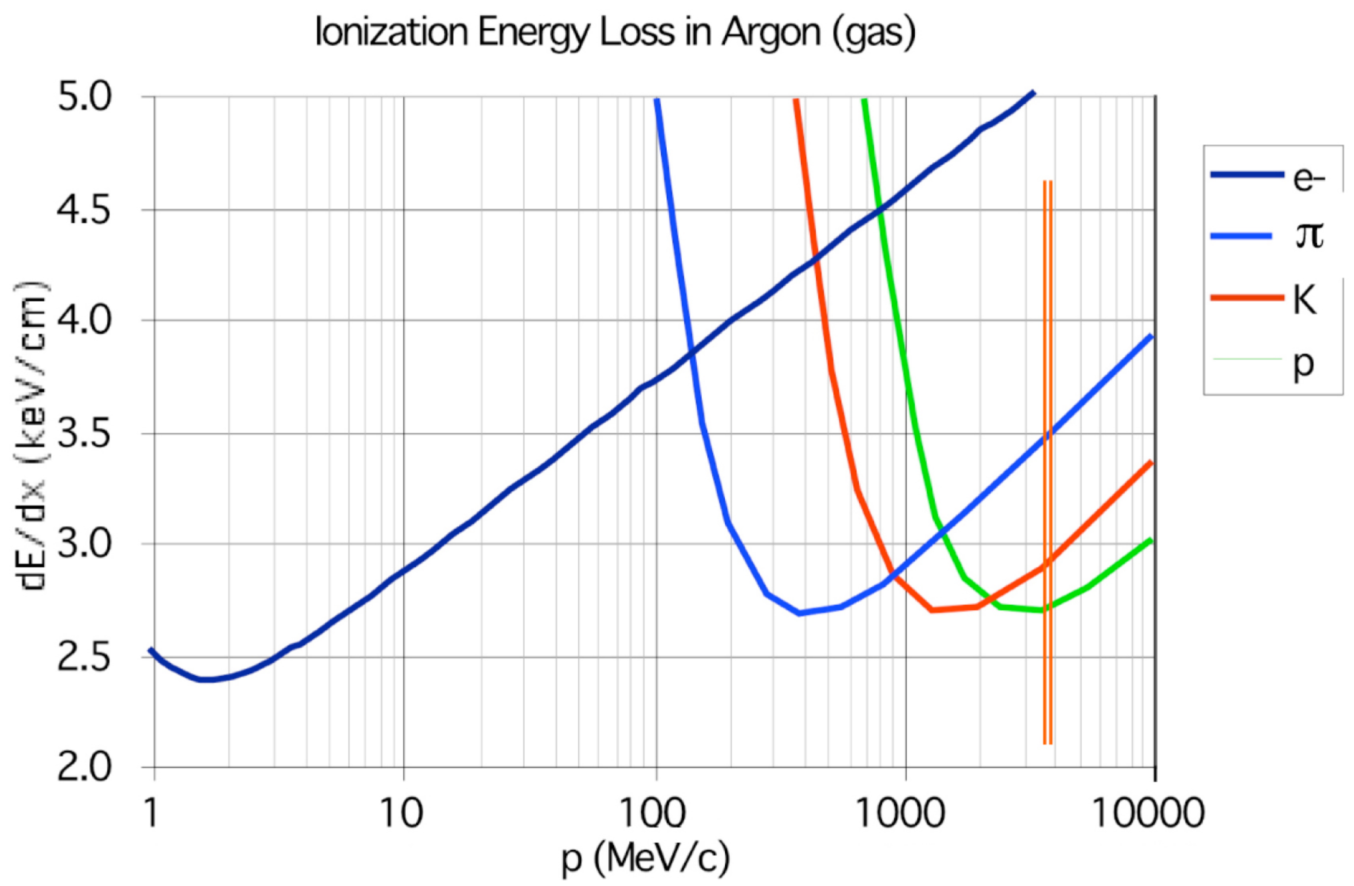



Figure 9.23: Particle identification based on differences in specific ionization ($\langle dE/dx \rangle$) for particles with the same momentum, but different mass.

$$\langle \frac{dE}{dx} \rangle = K_{\mathrm{BB}} \frac{z^2 n Z}{\beta^2} \left[ \ln\left( \frac{2 m_e \beta^2 c^2}{\bar{I}} \right) \right]$$

Bethe-Bloch equation for non-relativistic particles

# Time of Flight

## Particle Identification

- Another method that is perfectly suitable for non-relativistic particles is based on a measurement of the time of flight between two points
- Particles with the same momentum, but different mass travel at different speeds
- The time it takes them to travel from point A to point B varies accordingly
- Measurements in a secondary beamline at the CERN SPS (Figure 9.24)
- The time-of-flight was measured between two plastic scintillator counters separated by ~ 55 m, and the time resolution was ~ 300 ps
- The figure shows that at a momentum of 3 GeV/c, protons and kaons could be clearly distinguished from the lower-mass pions, muons and electrons
- At a momentum of 8 GeV/c, it was not well possible to obtain a meaningful particle identification in this setup

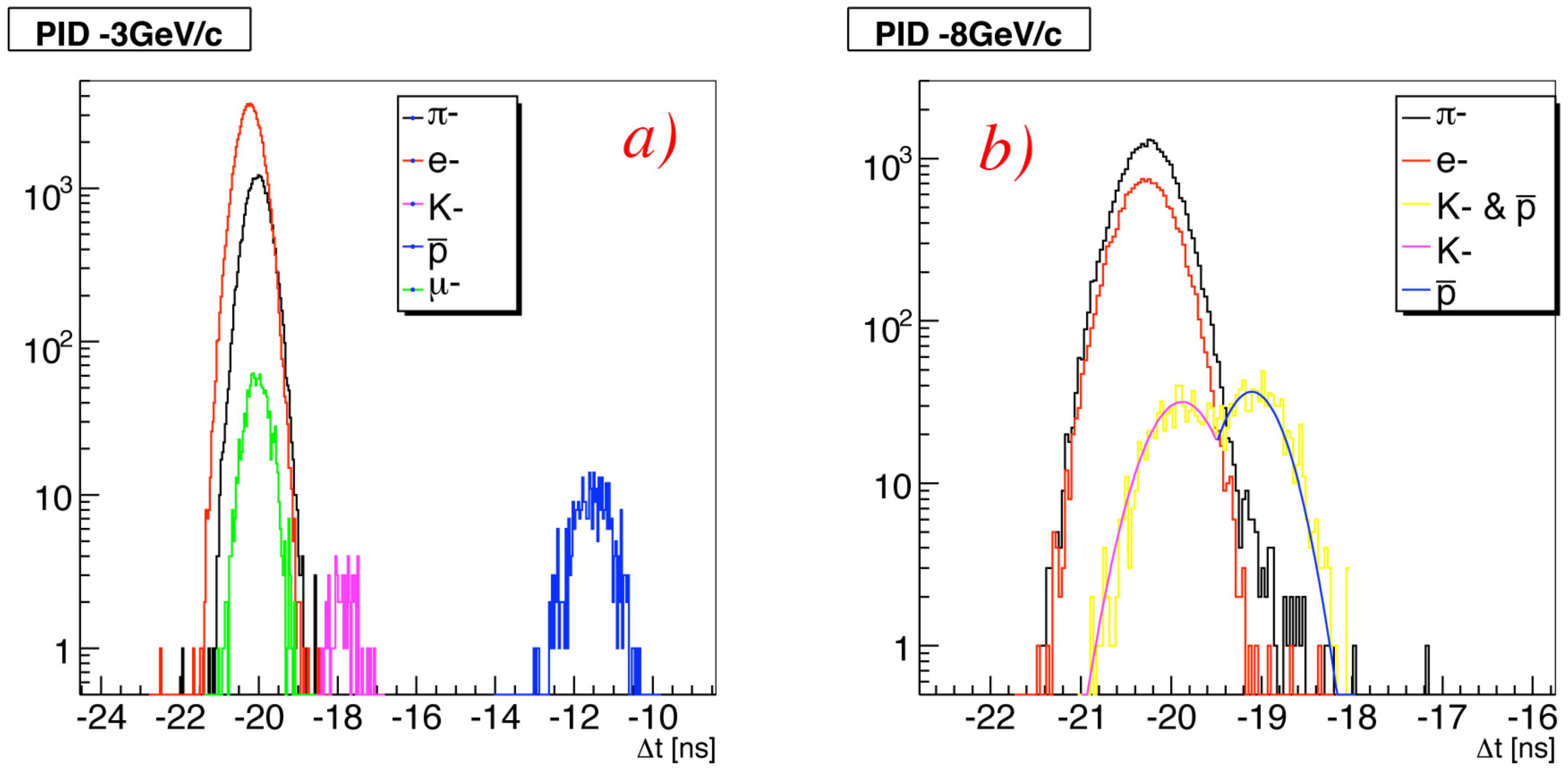



Figure 9.24: Particle identification based on a time-of-flight measurement. The particle momenta were 3 GeV/$c$ ($a$), or 8 GeV/$c$ ($b$).

# Cerenkov Signals

## Particle Identification

- In experiments at $e^+e^-$ storage rings, Ring Imaging Cerenkov counters are used, for example to identify kaons and to distinguish between pions, protons and kaons
- A particle traveling faster than c/n emits light at a characteristic angle $\theta = \arccos(n\beta)^{-1}$ with the direction of the particle
- These photons thus form a ring with an opening angle θ that depends on the velocity of the particle

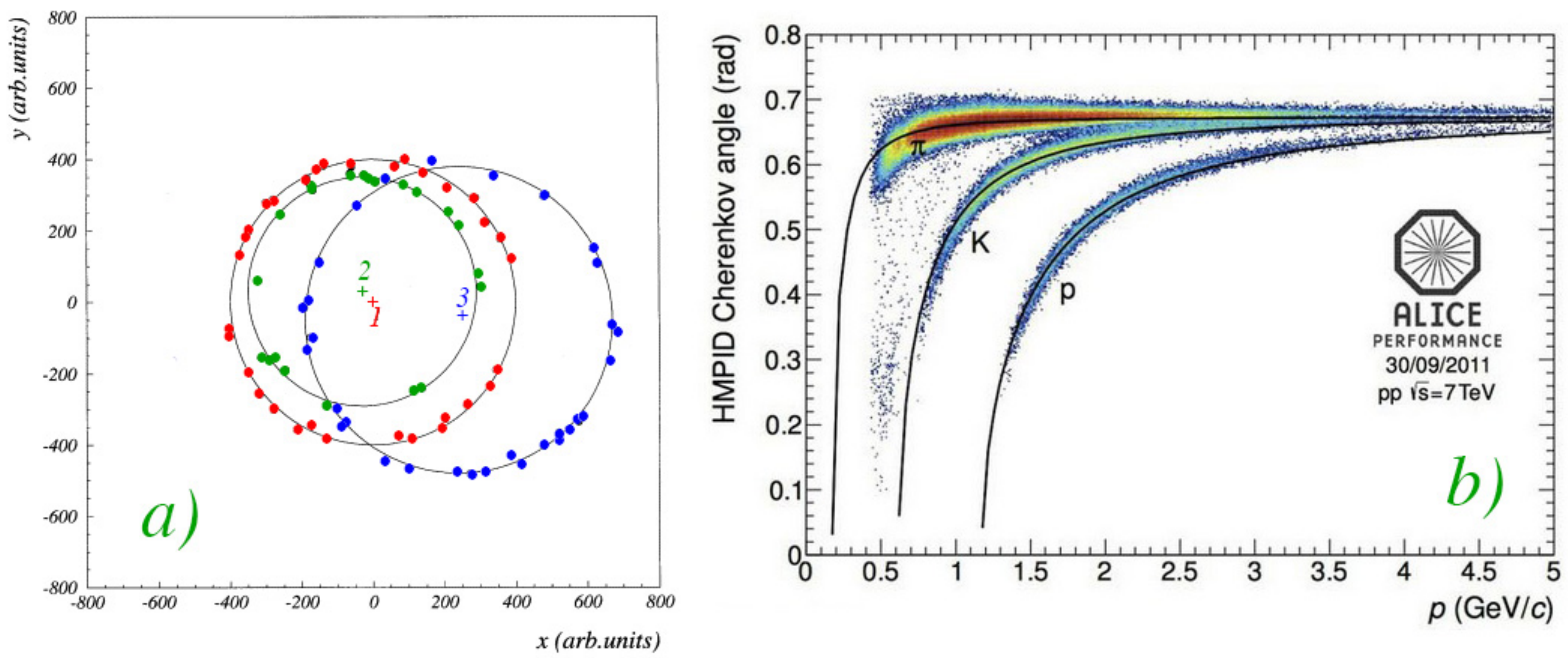



Figure 9.25: Hit patterns in a RICH counter, with three Čerenkov rings fitting this pattern ($a$). The opening angle of Čerenkov rings for pions, kaons and protons as a function of momentum, for the RICH detector in the ALICE experiment at CERN's LHC ($b$).

# Methods used in calorimetry

## Particle Identification

- Figure 9.26 (a):by measuring the signal in a thin preshower detector placed in front of the calorimeter, a clear distinction appears between hadrons, which deposit very little energy in this device and electrons which start their shower development in it and therefore produce larger signals
- The time structure of the signals is used to distinguish between electrons (which all produce pulses with the same time structure) and hadrons, whose pulses are typically considerably wider in this particular device (SPACAL, a lead/ scintillating-fiber calorimeter)

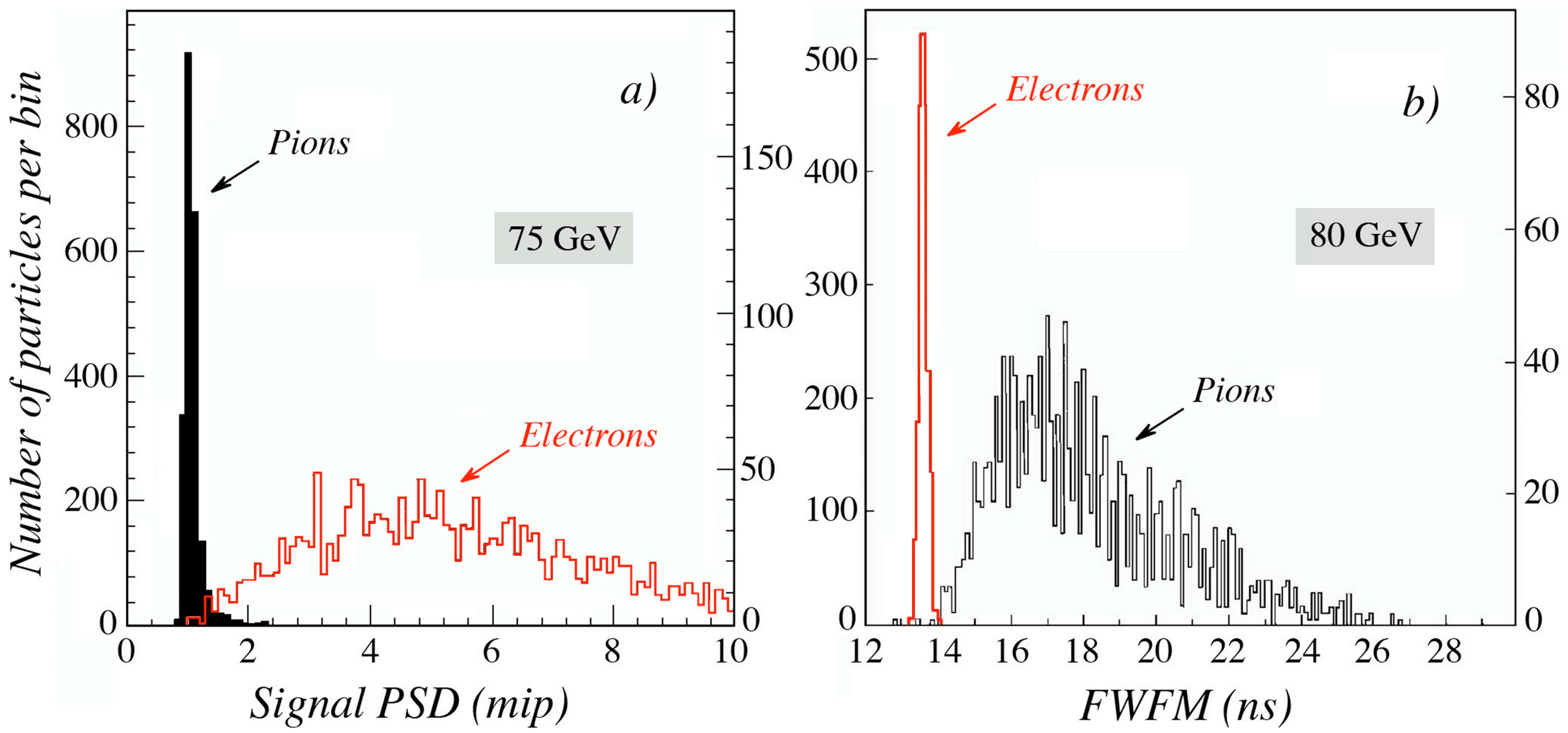



Figure 9.26: Two different methods to distinguish electrons from pions in a calorimeter. Diagram $a$ shows the signal distributions in a $2X_0$ thick preshower detector (PSD). In diagram $b$, the distributions of the duration of the pulse (here defined as the full width at one-fifth of the maximum amplitude) is plotted. In both diagrams, the left hand scale refers to the narrow distribution, the right hand scale to the broad one.

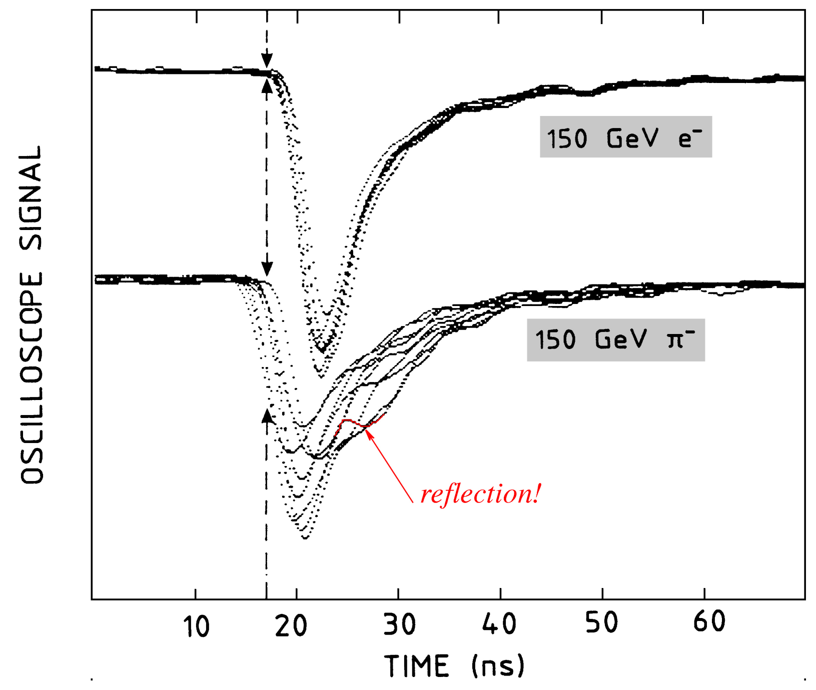



FIG. 5.50. SPACAL signals from 10 different electron and 10 different pion showers at 150 GeV [Des 89]. The time structure of the signals produced by pions interacting at different depths inside the SPACAL detector show the effect of the mirrored upstream fiber ends.

# Methods used used for highly relativisitic particles

# Particle Identification

- Transition Radiation can be used to identify and distinguish between highly relativistic particles
- It is emitted when extremely relativistic particles cross the boundary between two media with different indices of refraction
- The total energy loss of a charged particle in the form of transition radiation depends on its Lorentz factor
- Since γ = E/m, for a given momentum, the value of γ is inversely proportional to the mass of the particle.
- TRD radiation is therefore ideally suited to identify very-high-energy electrons

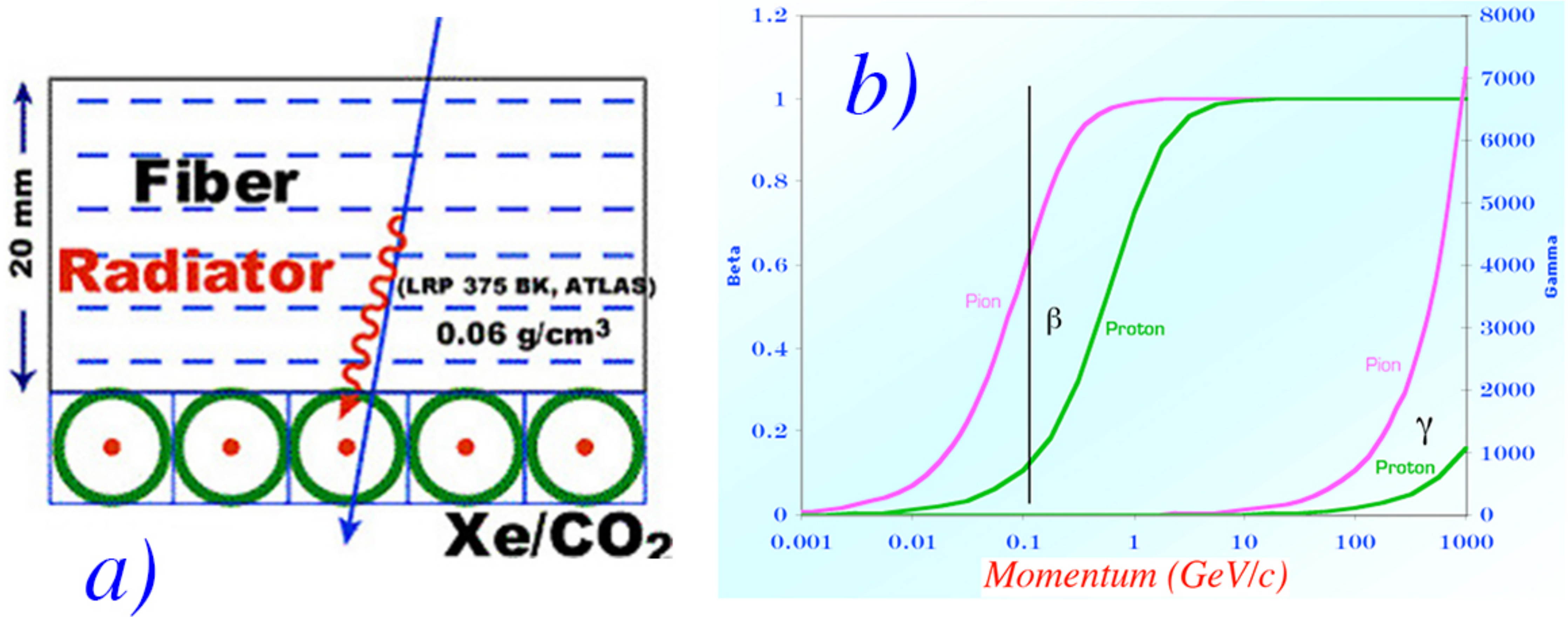



Figure 9.27: The Transition Radiation Detector of the ATLAS experiment consists of a fiber tracker. The TR $\gamma$s are detected in wired straw tubes filled with a high-$Z$ gas mixture ($a$). Particle identification based on differences in velocity ($\beta$) or the Lorentz factor ($\gamma$) for particles of the same momentum ($b$).

Transition Radiation