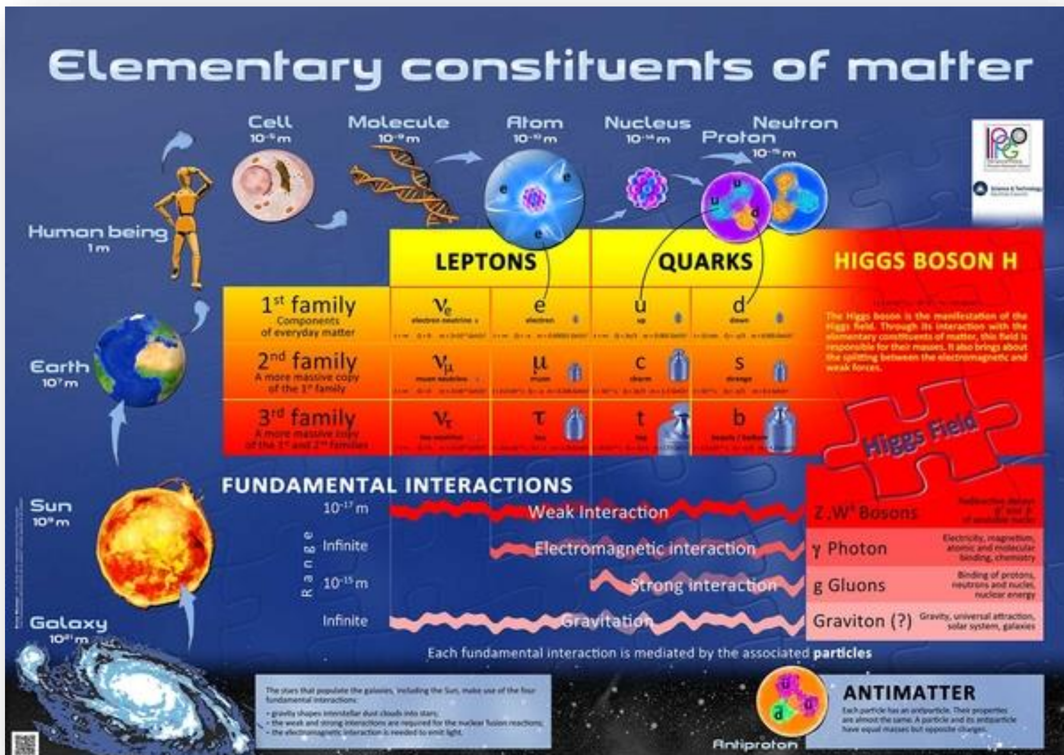
Physics of Particle Detectors

C. Mariñas
Instituto de Física Corpuscular, IFIC (CSIC-UV)

Particle Detectors

Nuclear and particle physicists need to detect and measure the properties of the particles (or its absence) in all our experiments → Particle detectors

We are talking here about the fundamental particles described by the Standard Model (and beyond)

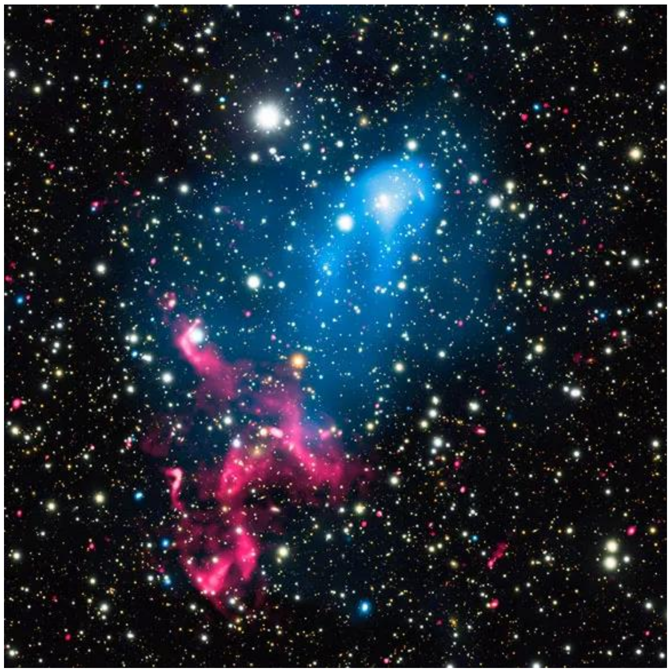


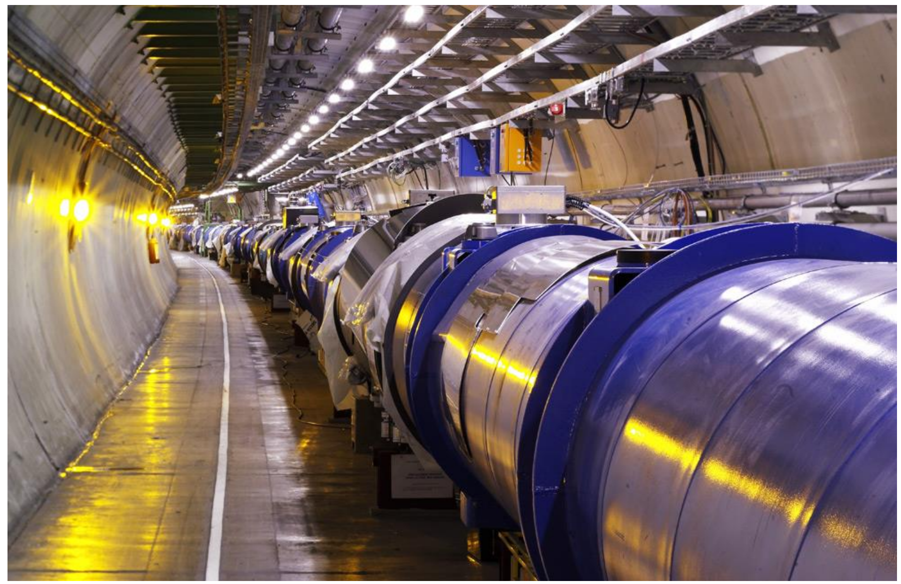
Accelerators: Cosmic and human-made

Two different ways of generating subatomic particles:

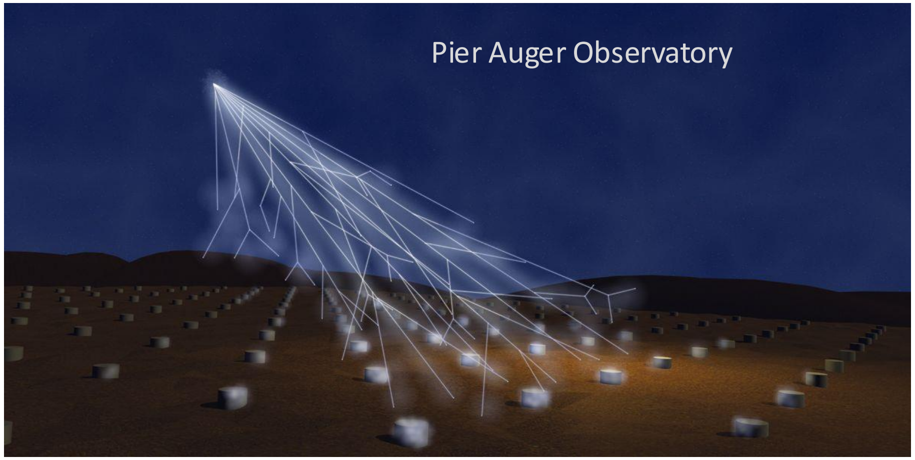
- One simple way of finding particles is to look at cosmic rays. This provides very high energy particles, but is a random process.

- The other way to generate these particles is using a particle accelerator, which manipulates particles using electrical and magnetic fields.



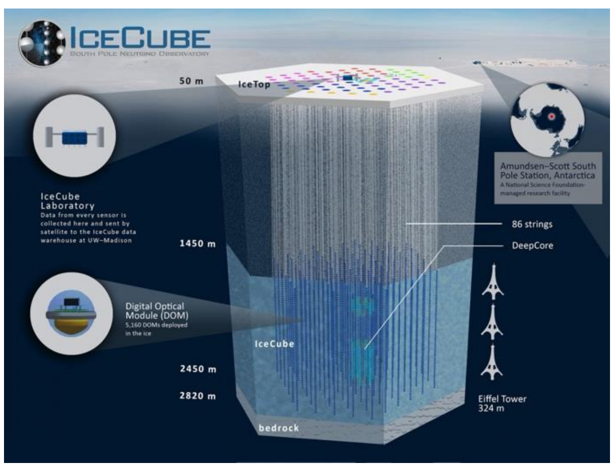


Astroparticle Physics Experiments

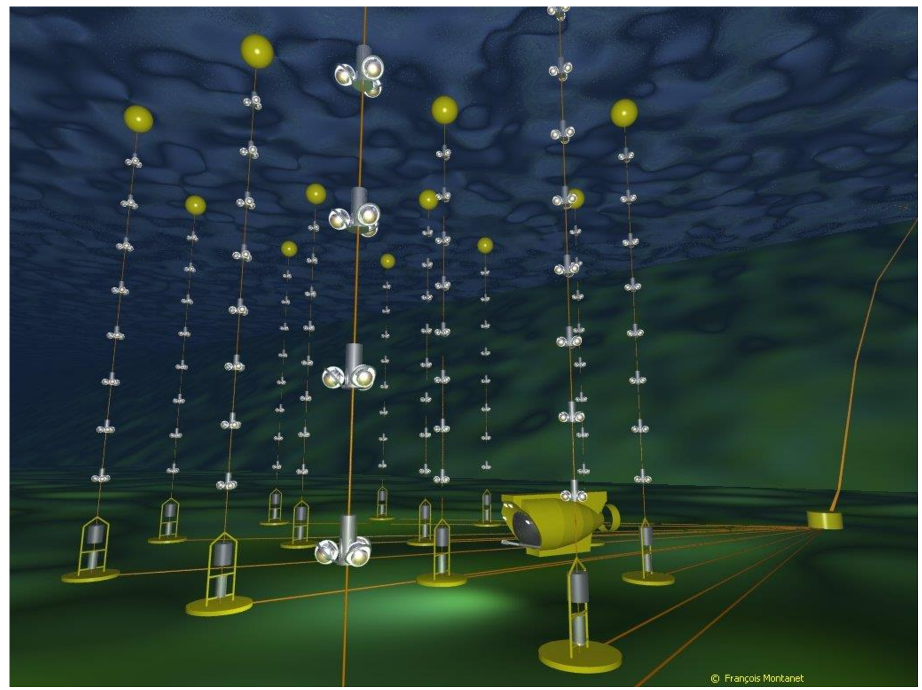


Investigate cosmic ray cascades using the atmosphere as part of the detector

… also under see water or polar ice



ANTARES – KM3NeT

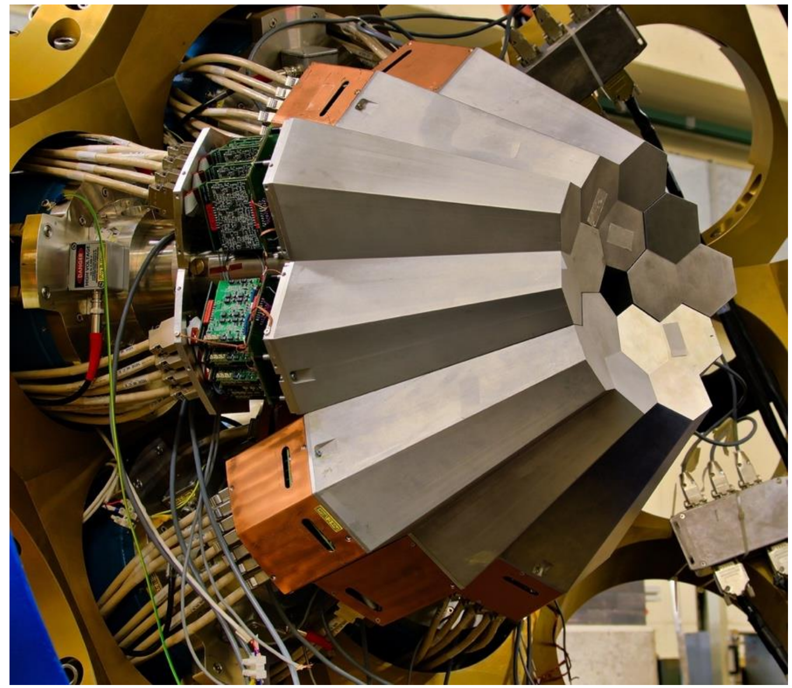


Nuclear Physics Experiments

For nuclear physics experiments, there are centers where isotopes are produced.

Specially important is the detection of gammas (high energy photons) produced by internal nuclear processes or neutrons

Neutron detector: n + ^{3}He -> p + ^{3}H

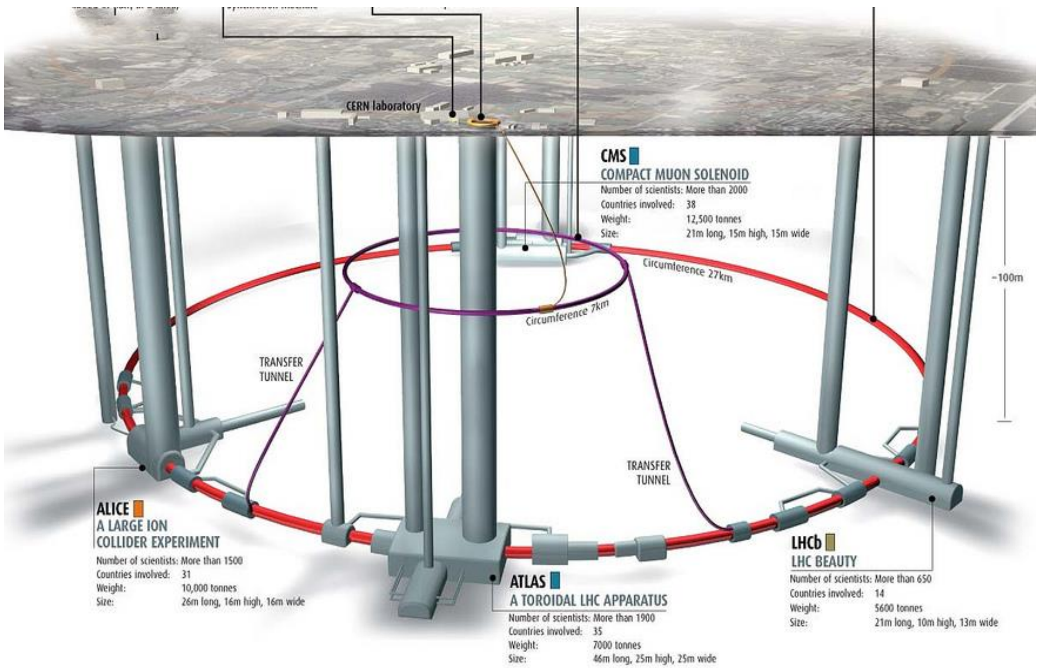


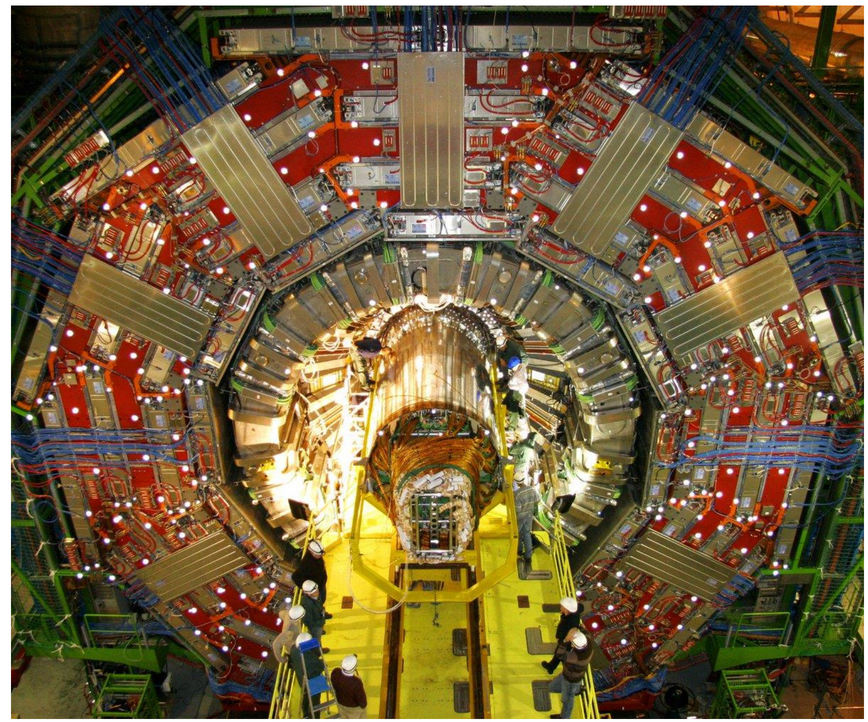
AGATA: **A**dvanced **GA**mma **T**racker **A**rray

Experimental High Energy Physics

Accelerator interaction region surrounded by big general purpose experiments

Big (tens of meters) experiments made by large international collaborations over decades with specialized detectors working in a coordinated manner





Much closer to us, these detection techniques are used at hospitals to detect (PET, CT, …) and treat tumors (hadron therapy, …).

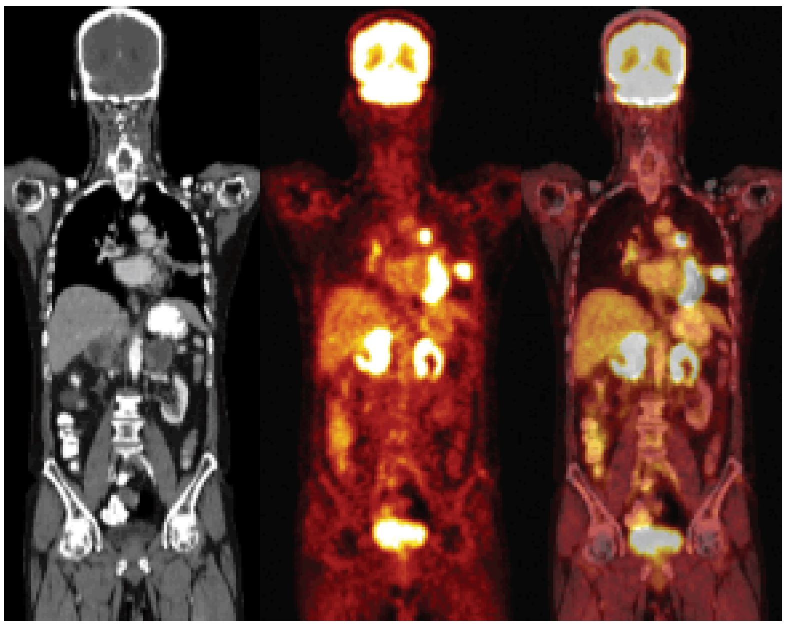
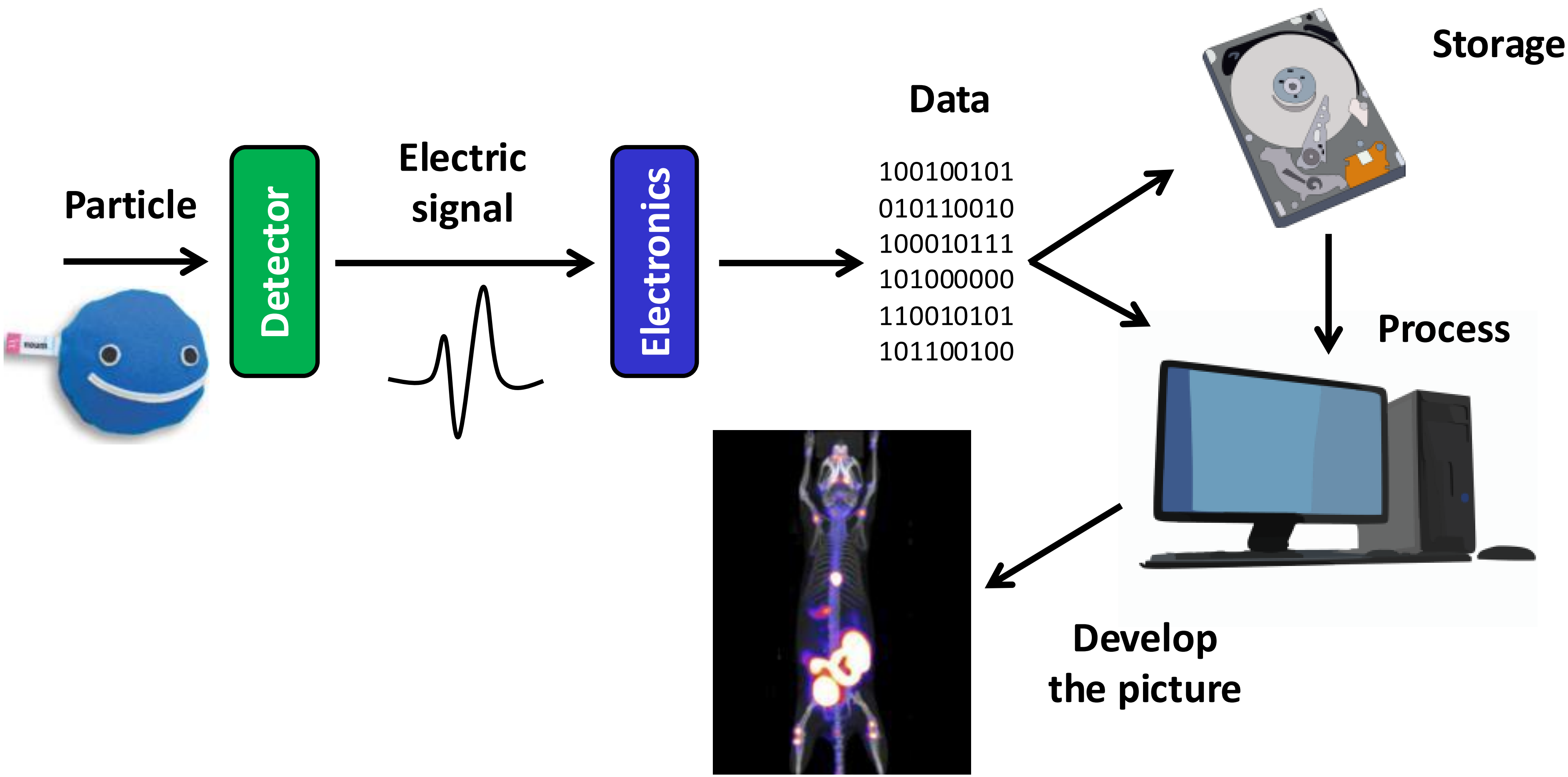


FIGURE 1. CT, PET, and PET/CT of lung cancer with adrenal metastases.

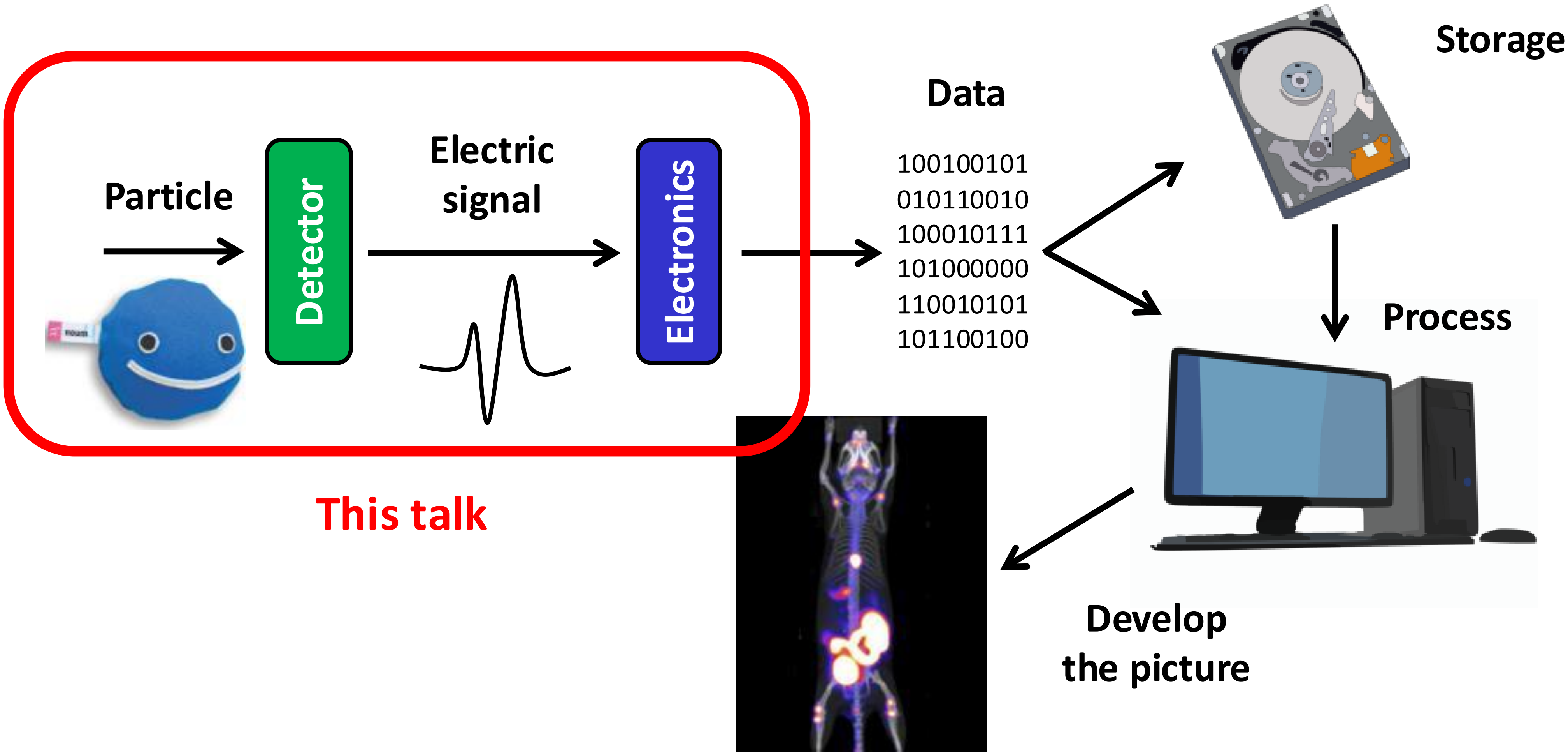
The Detector Chain

Detector physics: Multidisciplinary area of knowledge involving several fields



The Detector Chain

Detector physics: Multidisciplinary area of knowledge involving several fields



Why Particle Detectors?

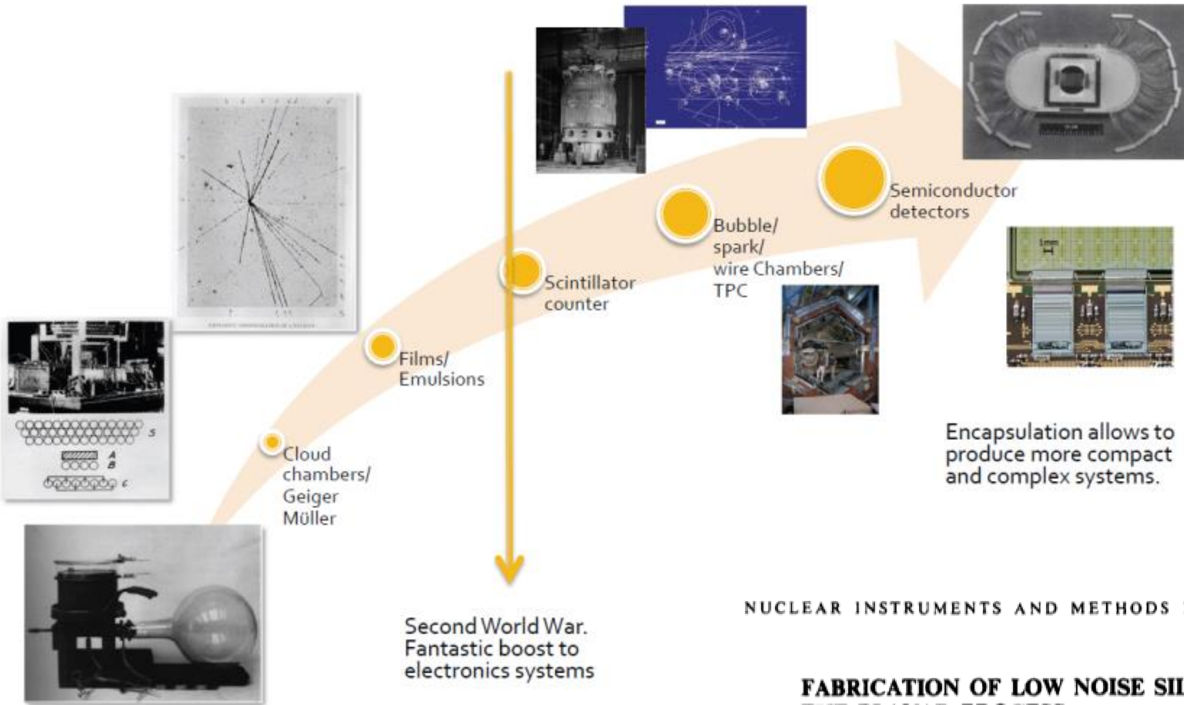
In particle physics, the processes occur on a scale that is either too brief or too small to be observed directly.

We can not see or touch the particles... So, we need some tools through which, indirectly, study those processes.

In particle physics, a **particle detector** is a device used to detect, track, and/or identify high-energy particles.

→ Types of radiation and interaction with matter

Particle Detector Developments



1979: the birth of the semiconductor era
First use of planar process developed for chip industry in a fixed target experiment with a planar diode

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

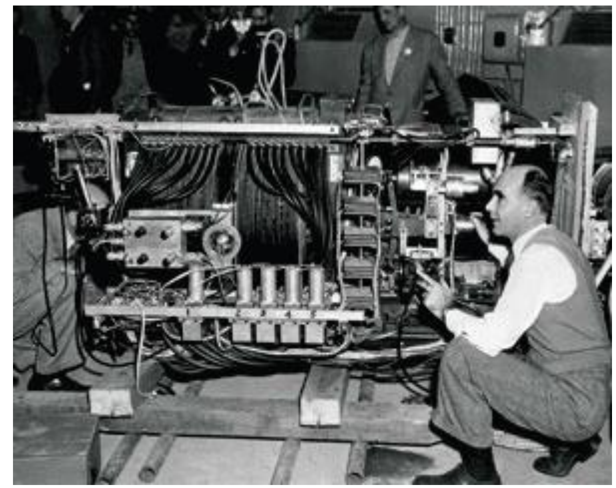
Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

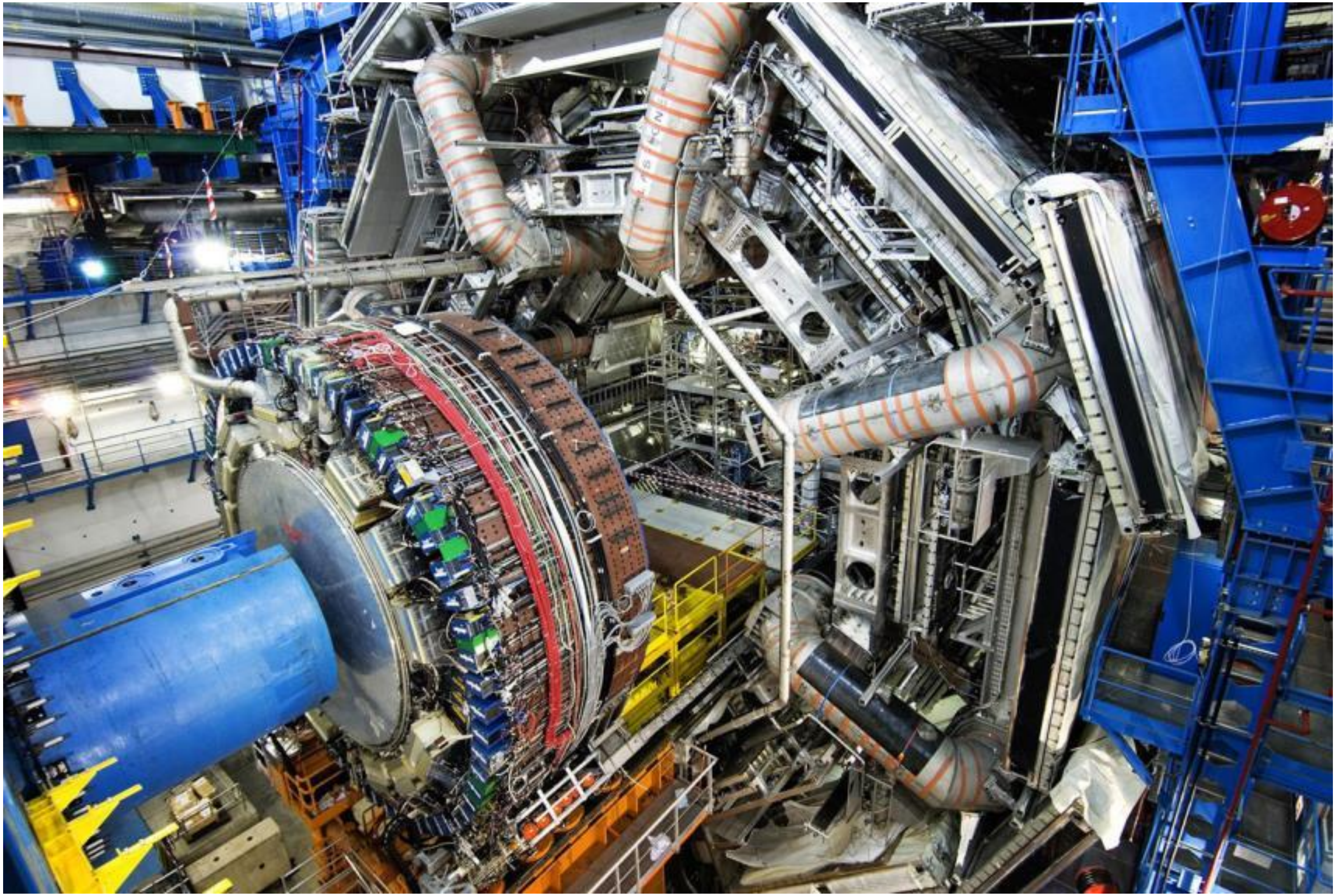
Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22 °C using 5 × 5 mm^2 detector chips

Cloud Chamber (1932)

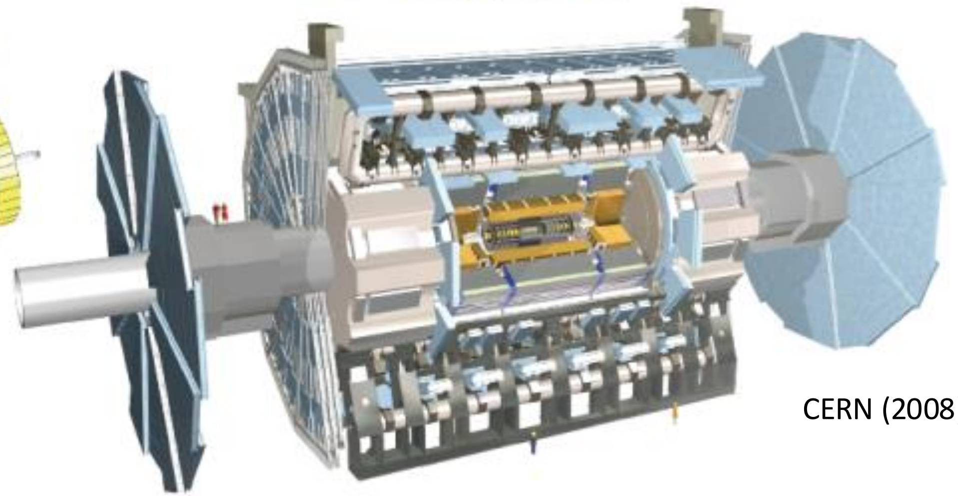


ATLAS (Nowadays)



Detector Complexity Evolution

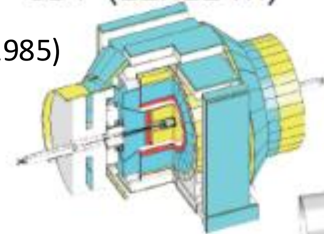
ATLAS (25x40 m)



CERN (2008)

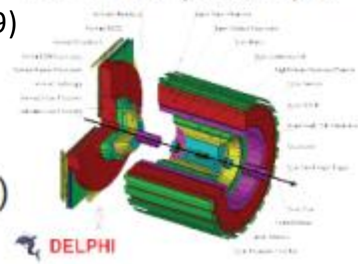
CDF (12x12 m)

Fermilab (1985)



DELPHI (10x10)m

CERN (1989)



PLUTO (4x4 m)

DESY (1977)

SLAC (1973)

Mark I (4x4 m)

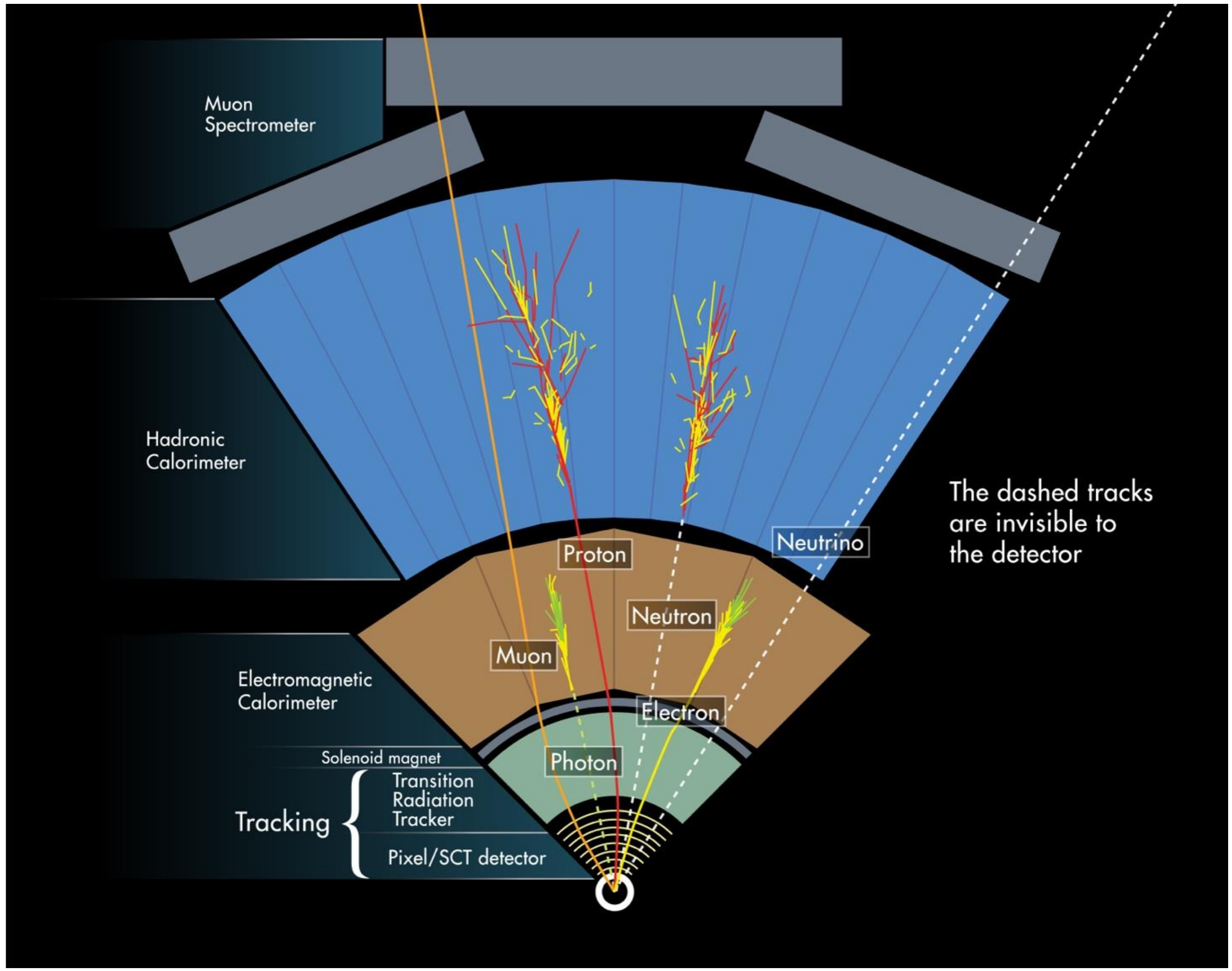
The size and complexity of the detectors have grown considerably and so the way the scientific community develops the HEP detectors

General Purpose Detector

$$E = \sqrt{(mc^2)^2 + (pc)^2}$$

- Energy (E)
  Calorimeters
- Mass (m)
  Particle ID systems
- Momentum (p)
  Vertex and trackers

Specialized detector systems exploiting the different way particles interact with matter

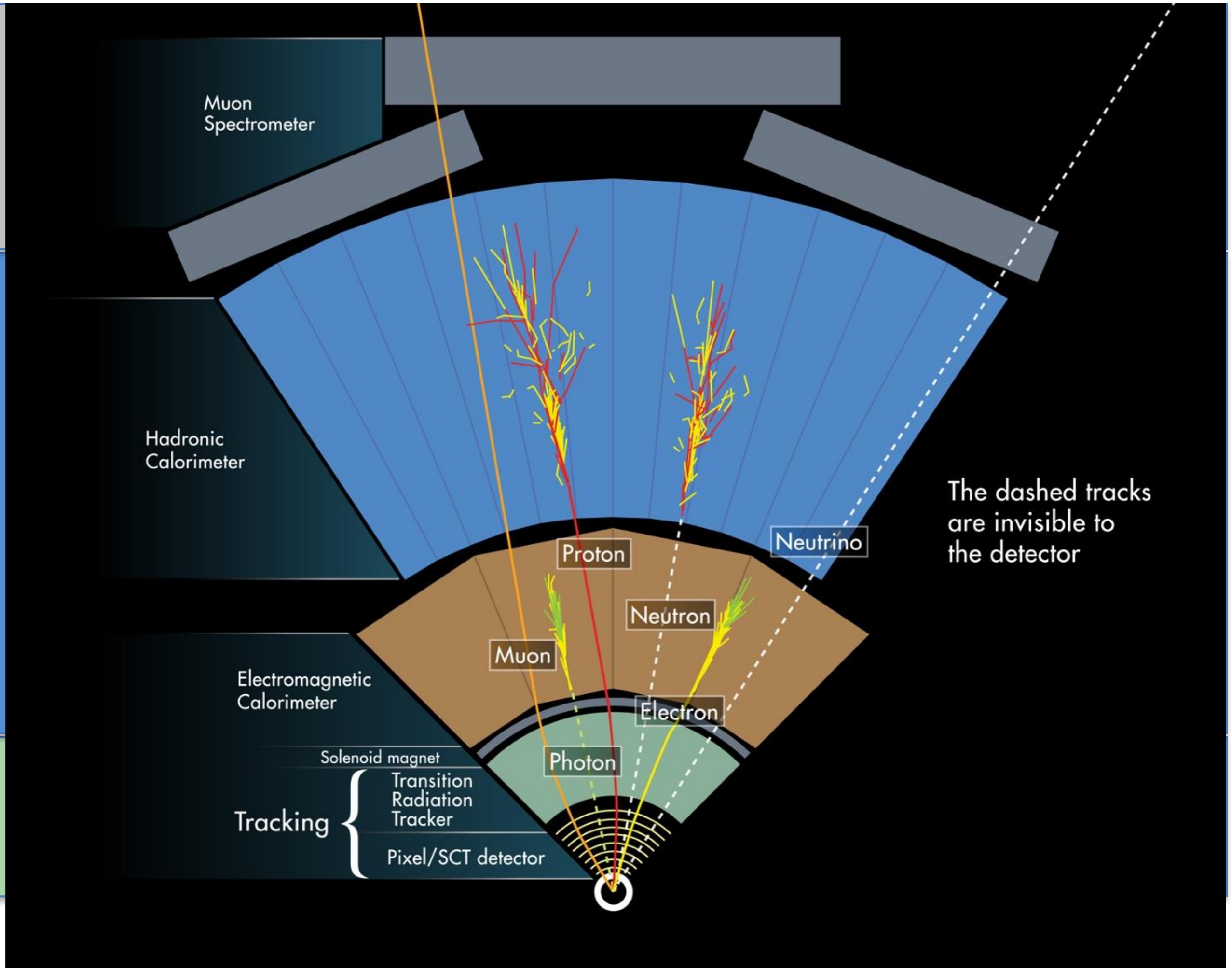


General Purpose Detector

Muon System

Calorimetry

Tracking + Magnet



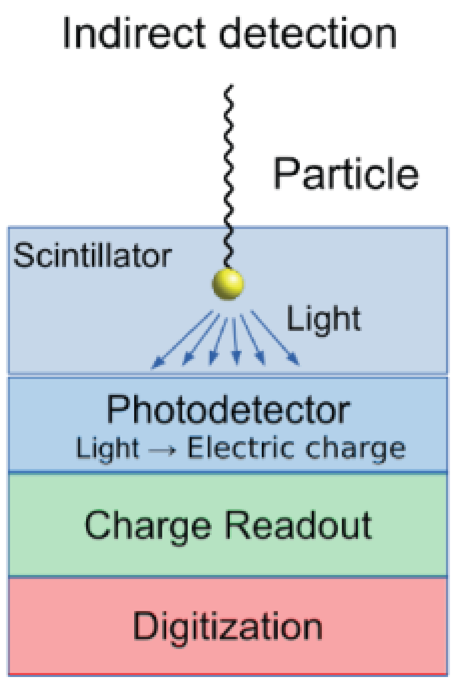
A Particle Detector

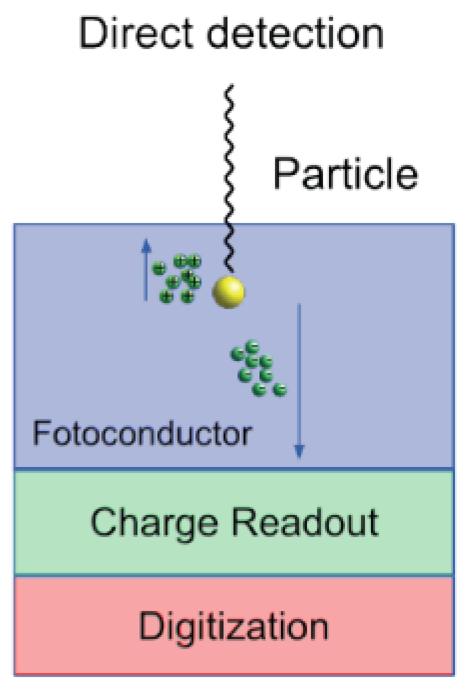
- In order to detect a particle:
  - It must interact with the material of the detector
  - Transfer energy in some recognizable fashion

- The detection of particles happens via their energy loss in the material it traverses

- Our goal is: Convert the energy deposited in an electrical signal we can play with

The deposited energy excites the medium that decays by emission of light which in a second step is converted into charge



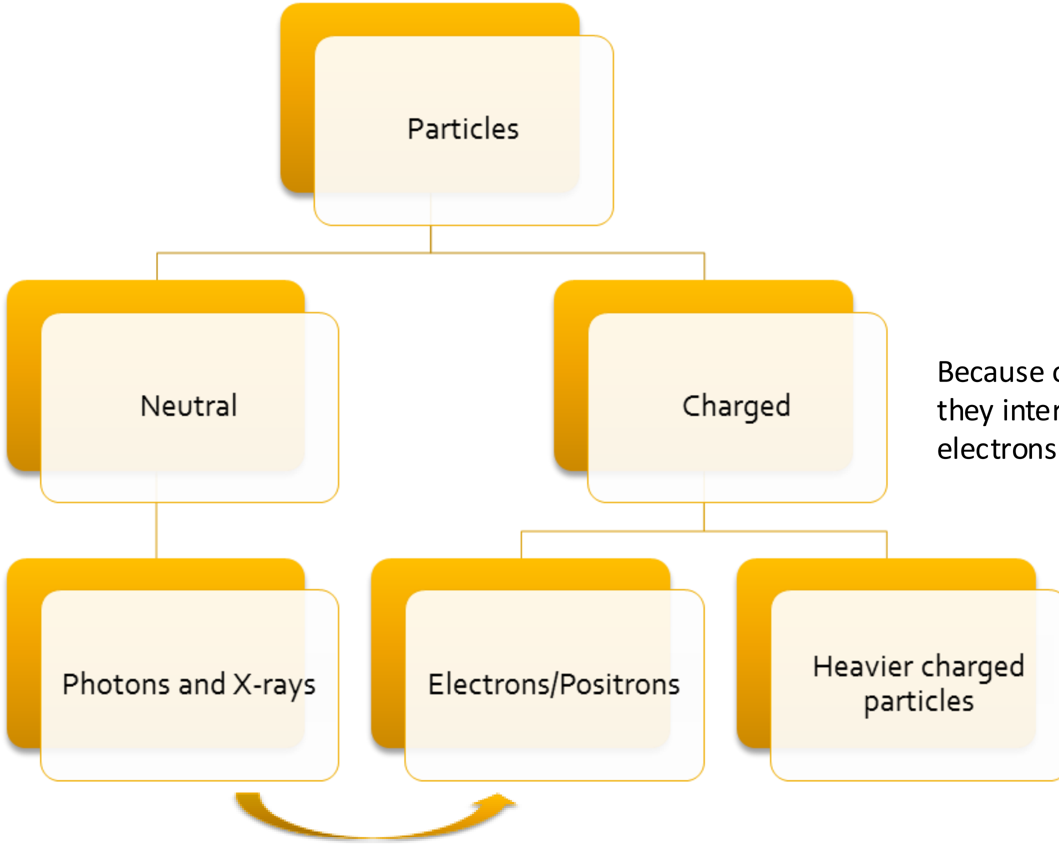


The ionization creates mobile charges that we can detect

Interaction Of Particles With Matter

Interaction of particles with matter is the basis of all particle detection devices

Neutral particles exhibit one-off interactions, producing charged particles



Because of the electric charge, they interact continuously with the electrons in the medium

- Charged particles: Ionization, Bremsstrahlung, Cherenkov, …
- Photons: Photoelectric effect, Compton, pair production
- Neutral hadrons: Nuclear interactions
- Neutrinos: Weak interactions

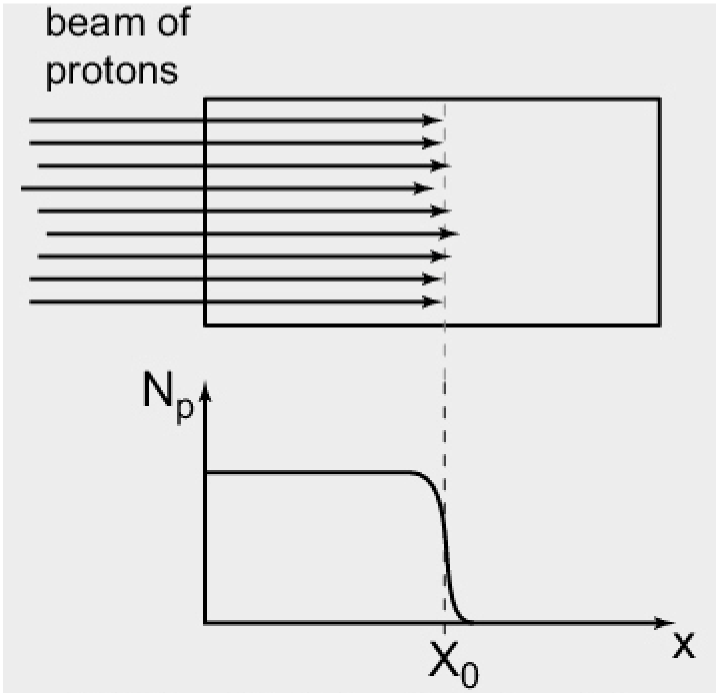


Abbildung 2.1: Schematisch dargestellte Eindringtiefe eines Proton-Strahls in Materie.

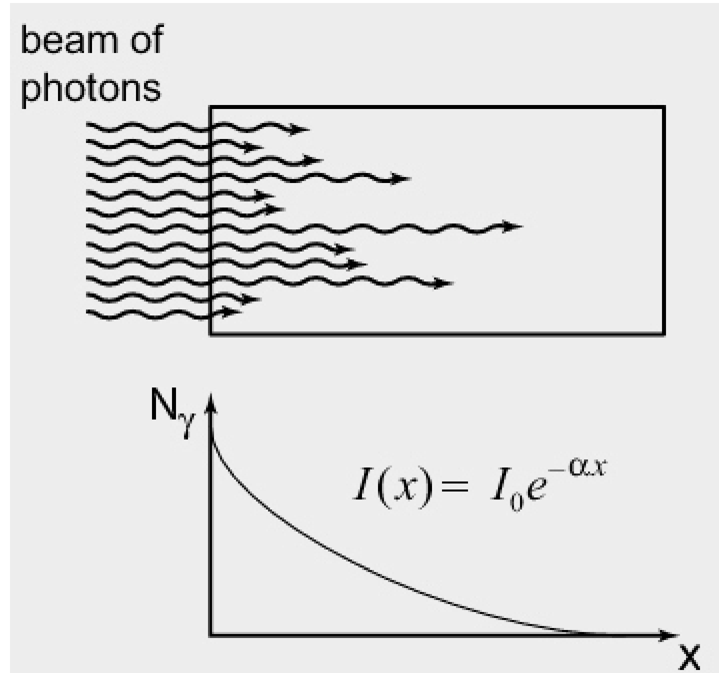
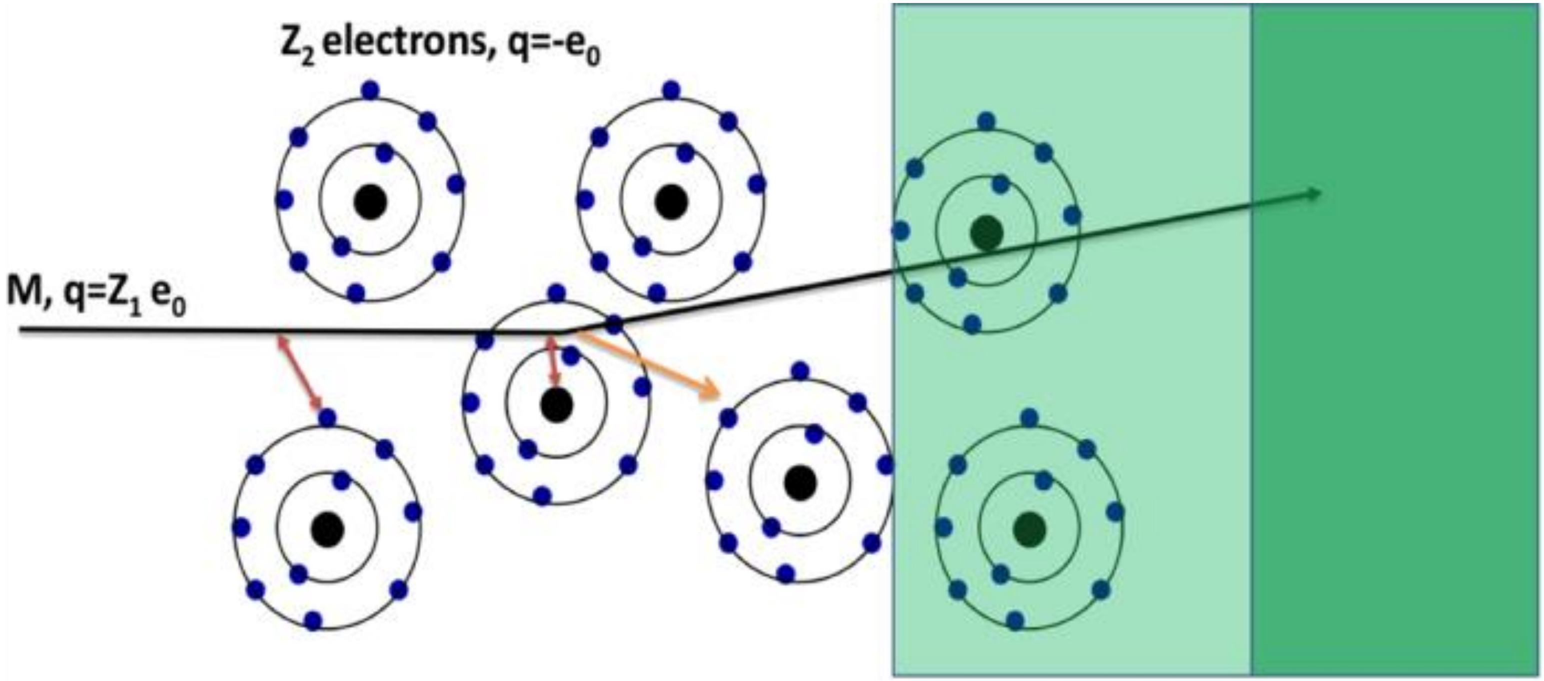


Abbildung 2.2: Wechselwirkung von Photonen mit Materie.

Interaction Of Charged Particles With Matter

Energy Loss Charged Particles



① Interaction with the atomic electrons. The incoming particle looses energy and the atoms are excited or ionized

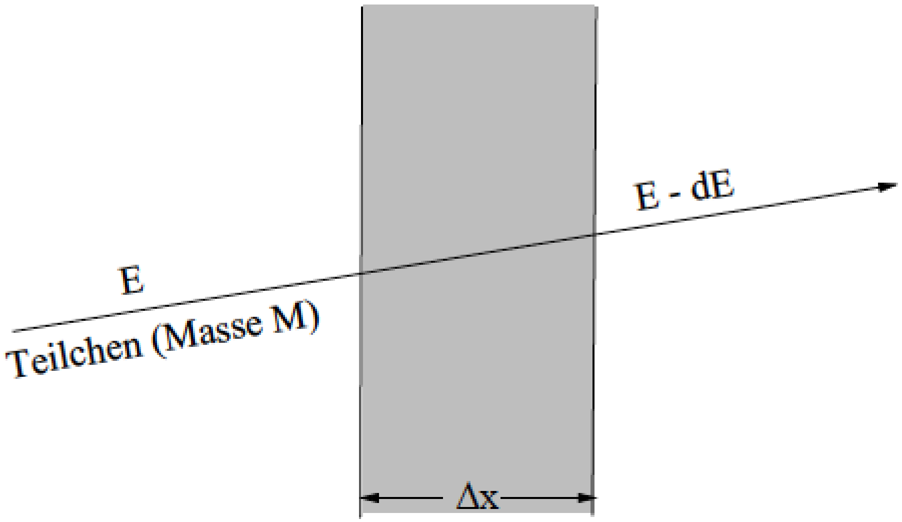
② Interaction with the atomic nucleus. The particle is deflected causing multiple scattering. Bremsstrahlung

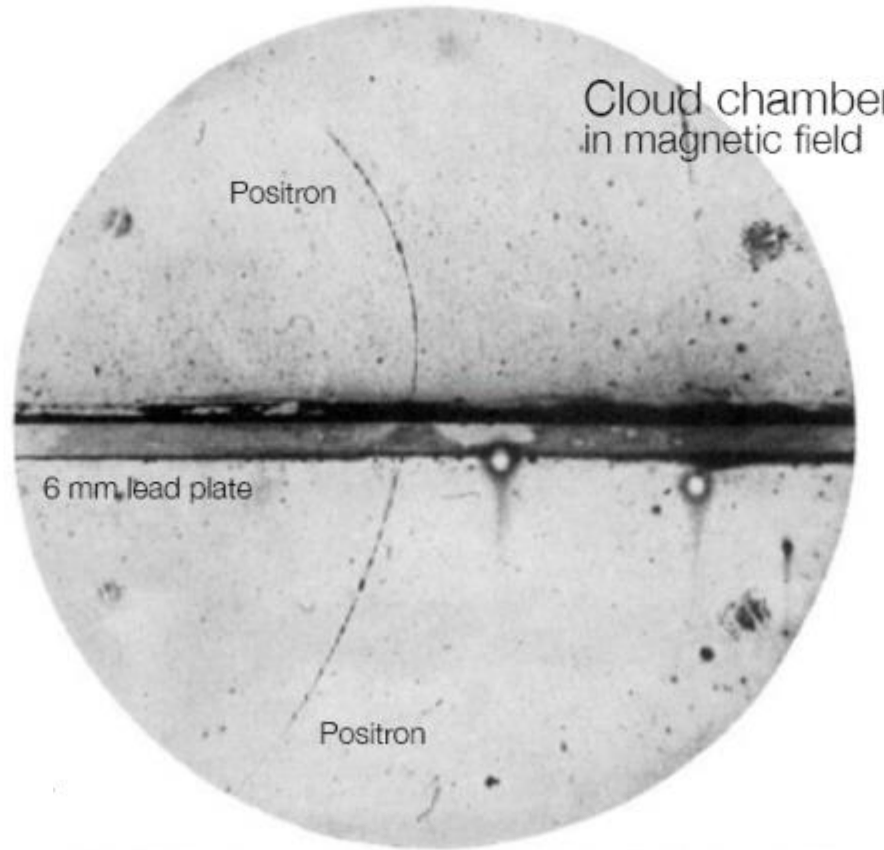
③ Cherenkov or Transition Radiation

- Charged particles loose their energy mainly by ionization of the atoms of the medium
- We can ‘calculate’ the average energy loss per unit of length dE/dx

Bethe Bloch Formula

Describes the energy loss of a **heavy charged** particle in matter.





- Magnetic field 1500 Gauss
- Chamber diameter 15 cm

- A 63 MeV positron passes through a 6 mm lead, leaving the plate with an energy of 23 MeV.

Bethe Bloch Formula: Features

Describes the energy loss of a **heavy charged** particle in matter.

The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad [\cdot \rho]$$

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

$m_e = 511$ keV
[Electron mass]

$\beta = v/c$
[Velocity]

$\gamma = (1-\beta^2)^{-2}$
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$

$M > m_\mu$

Bethe Bloch Formula: Features

Describes the energy loss of a **heavy charged** particle in matter.

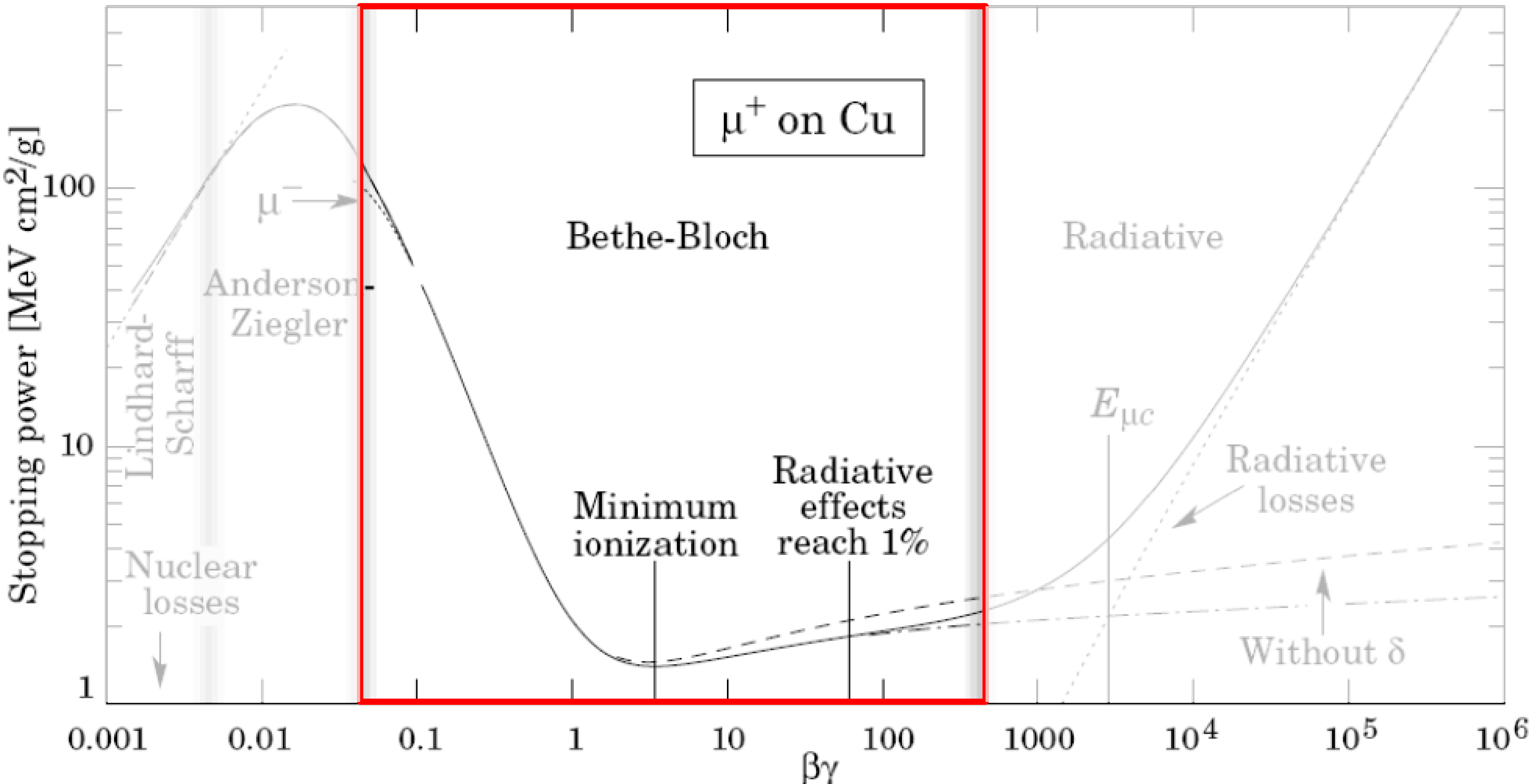
The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] [\cdot \rho]$$

density

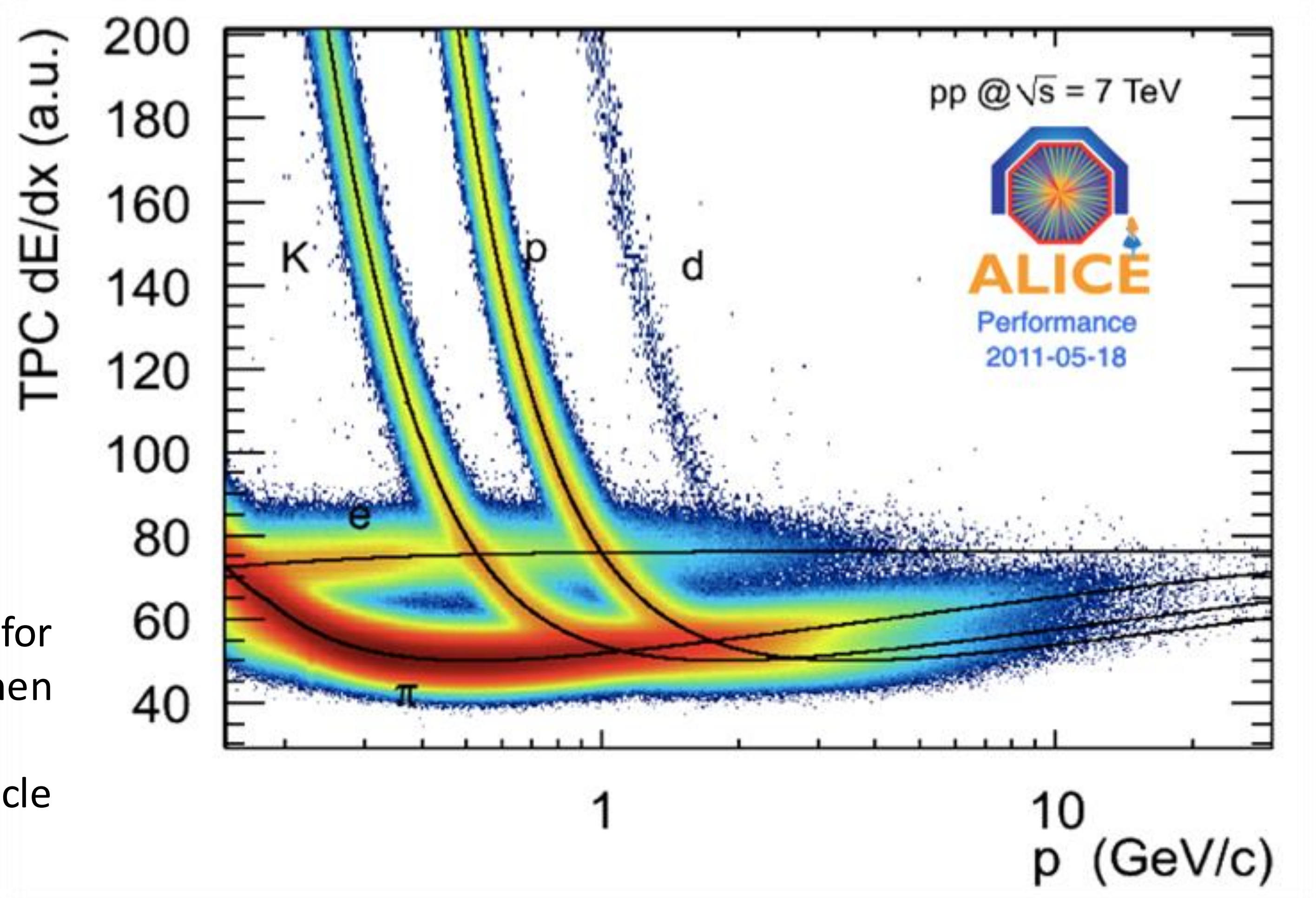
- Depends on $\beta\gamma$ = p/E·E/m=p/m of the projectile particle
- Depends on z^2, the charge of the projectile particle
- Same curve for all z=1 particles when plotted as a function of $\beta\gamma$
- Minimum at $\beta\gamma$=p/m~3 (v=96%c) → dE/dx~1.5 MeV/cm^{2}g
- Minimum ionizing particles (MIP) → Particles with $\beta\gamma$~3
- Depends only weakly on material (Z/A) at same $\beta\gamma$

Bethe Bloch Formula: Features



$\beta\gamma \sim 0.05$ $\beta\gamma \sim 500$

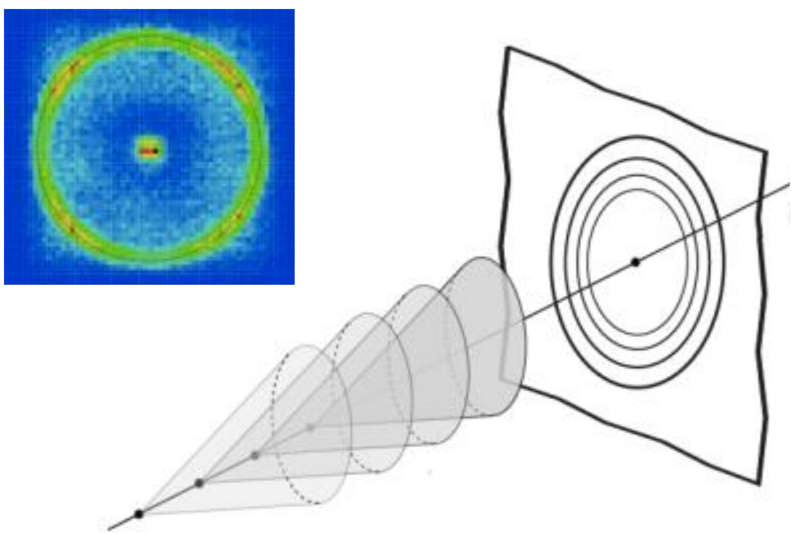
Bethe Bloch In Modern Detectors

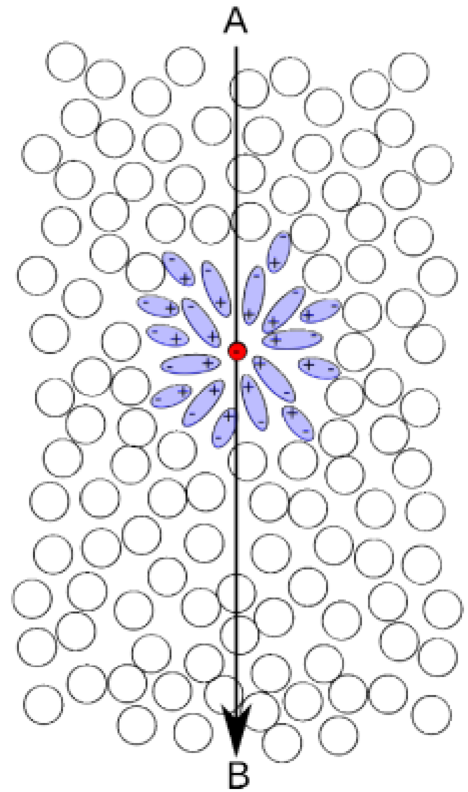


- Get different curves for different particles when plotted against *p*
- Possibility for particle identification

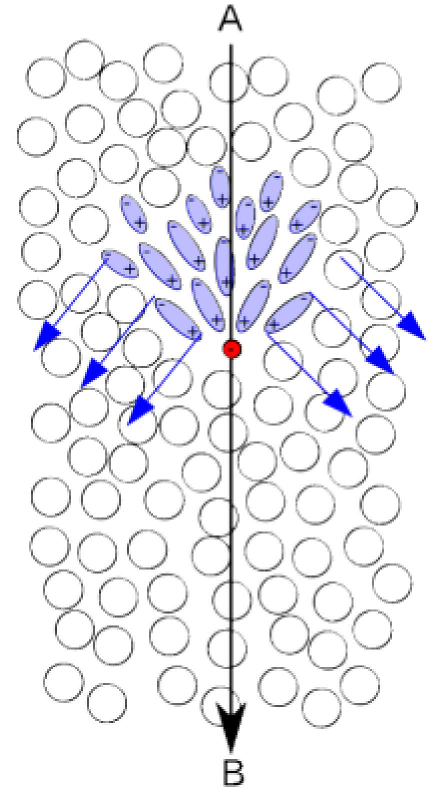
Cherenkov Radiation

- Cherenkov light is produced by particles traversing a 'radiator' faster than the speed of light in that media
- Radiation is emitted at a characteristic angle producing a cone of light
- Process not important for energy loss, but used in high-energy physics detectors
- We can detect the light with a photodetector





v < c/n
- Induced dipoles symmetrically arranged around particle path; no net dipole moment.
- No Cherenkov radiation

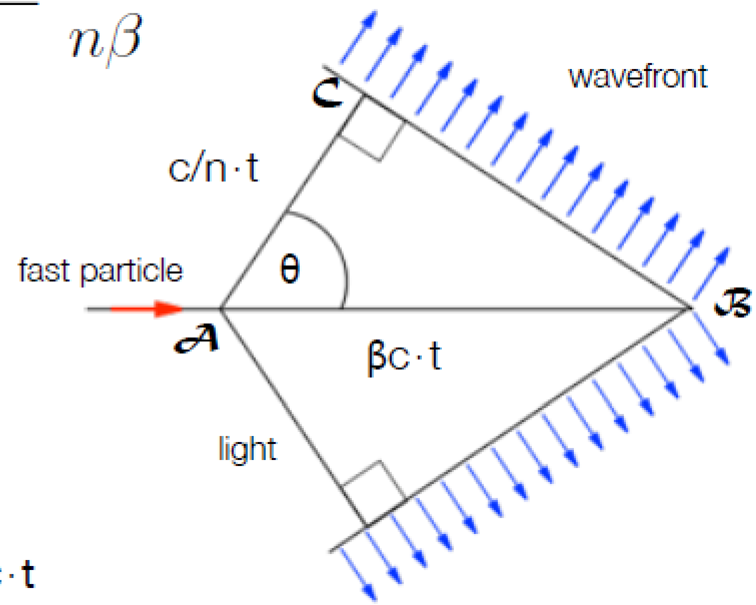


v > c/n
- Symmetry is broken and there is a constructive interference of electromagnetic pulses by polarization of the atomic dipoles.
- Radiation of Cherenkov photons

Cherenkov Radiation

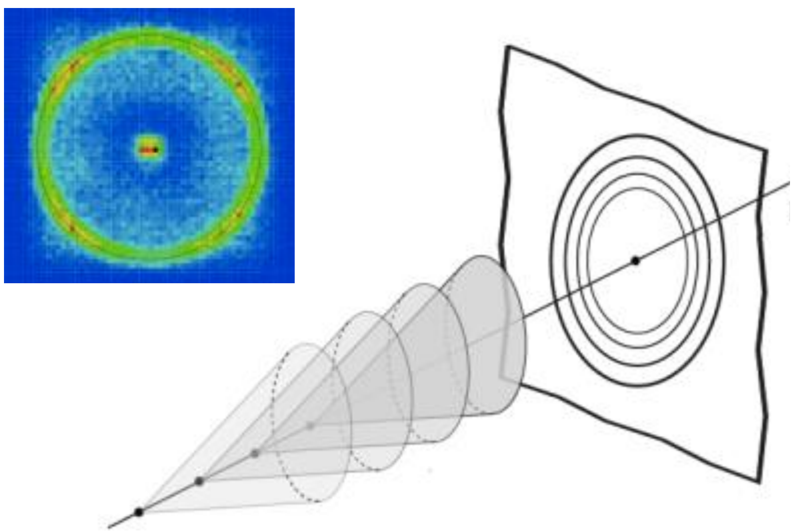
- Cherenkov light is produced by particles traversing a 'radiator' faster than the speed of light in that media
- Radiation is emitted at a characteristic angle producing a cone of light
- Process not important for energy loss, but used in high-energy physics detectors
- We can detect the light with a photodetector

$$\cos\theta_c = \frac{1}{n\beta}$$

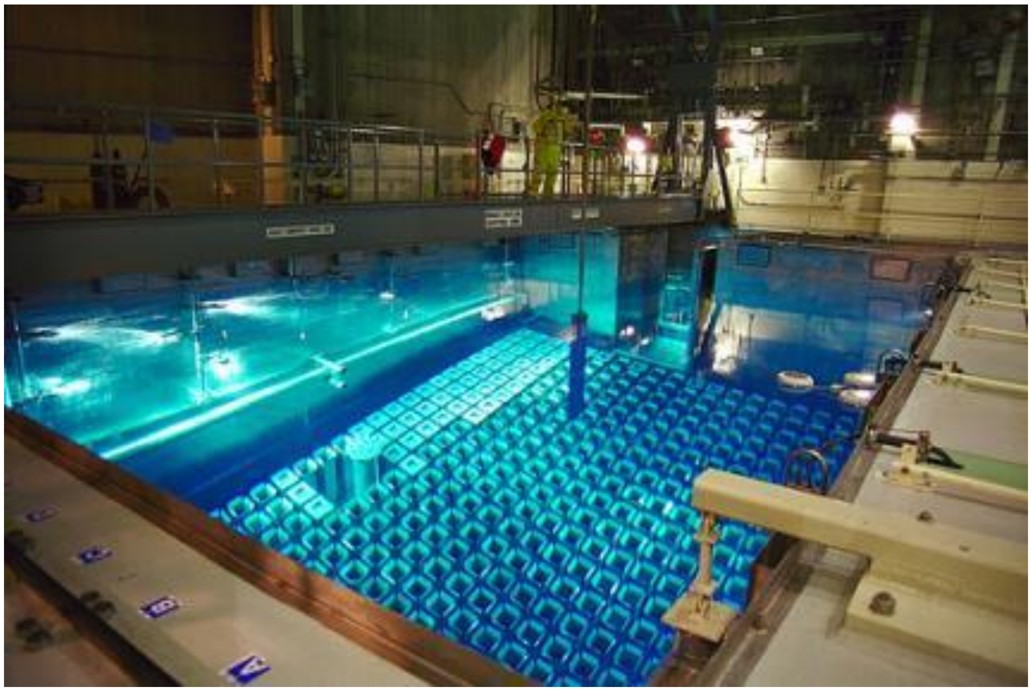


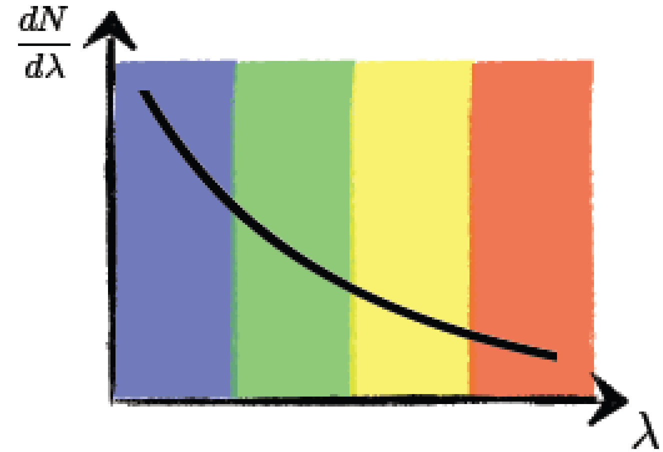
$$\mathcal{AB} = \beta c \cdot t$$
$$\mathcal{AC} = c/n \cdot t$$

$$\cos\theta = \mathcal{AC}/\mathcal{AB} = c/n \cdot t/(\beta c \cdot t)$$
$$= 1/n\beta$$



Cherenkov Radiation

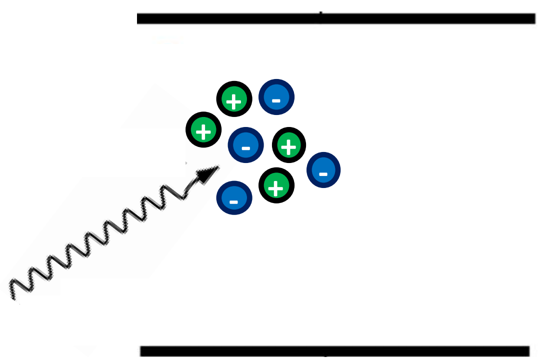




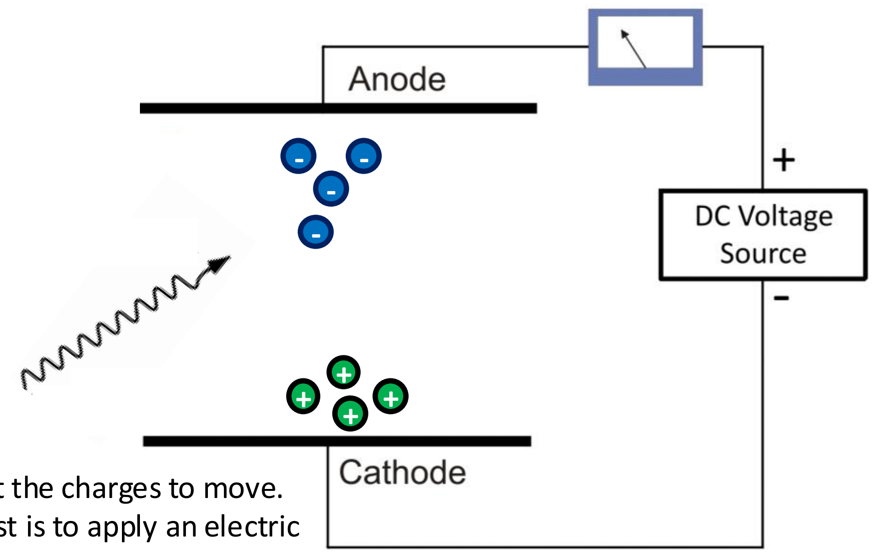
Gas-Filled Ionization Detectors

Schematic Principle

- Ionization creates charges in the detector volume:
  - Electron-ions in a gaseous detector (eh-pairs in a semiconductor)
- Electric field applied to move the charges and ‘induce’ an electric current
- Depending on the field strength, secondary ionizations are possible (amplification)



Charges created at rest. Not really useful



We want the charges to move. The easiest is to apply an electric field in the detector volume

Direct Detectors

- Ionization creates charges in the detector volume:
  - Electron-ions in a gaseous detector
  - Electron-hole pairs in a semiconductor detector
- Electric field applied to move the charges and 'induce' an electric current
- Depending on the field strength, secondary ionizations are possible (**amplification**)

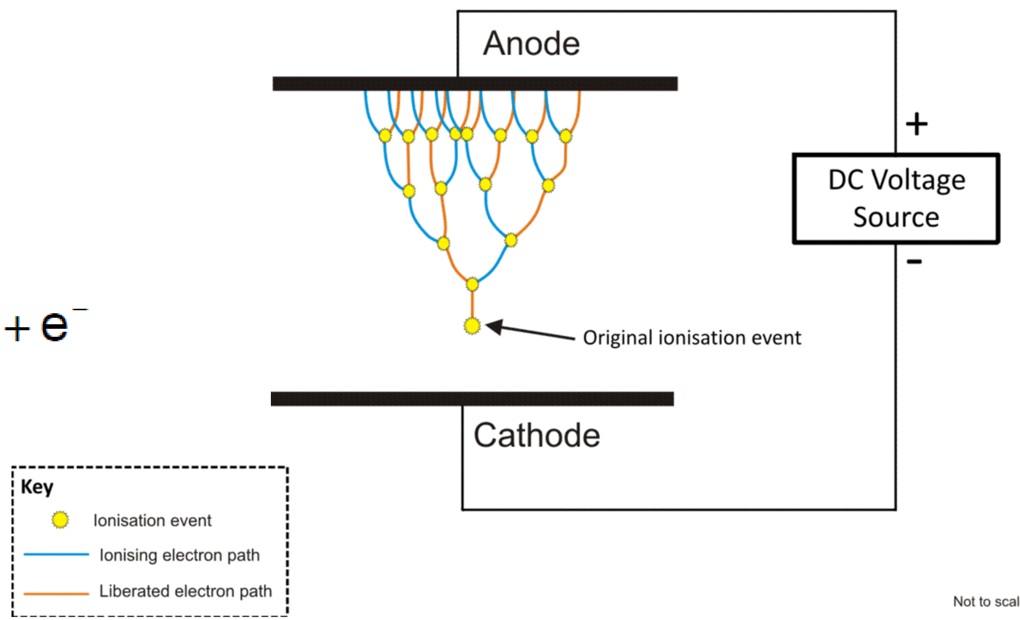
Primary ionization

$$X + p \rightarrow X^{+} + p + e^{-}$$

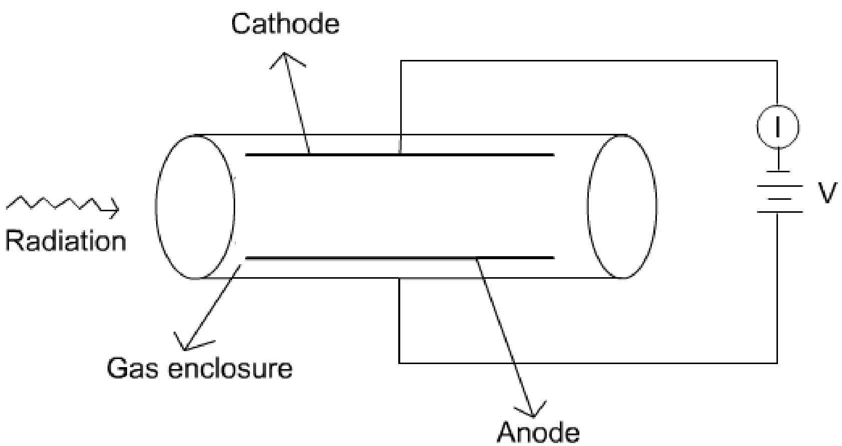
Secondary ionization

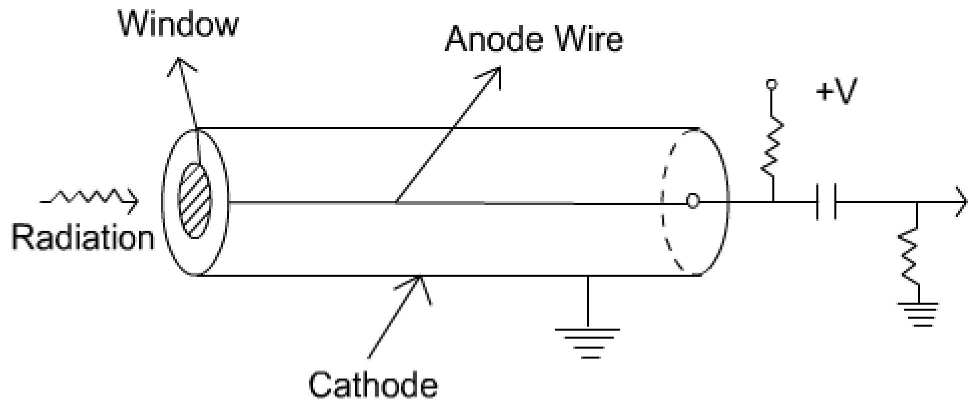
$$X + e^{-} \rightarrow X^{+} + e^{-} + e^{-}$$

p = charge particle traversing the gas
X = gas atom
e^{-} = delta-electron (δ)



Planar – Cylindrical Geometries



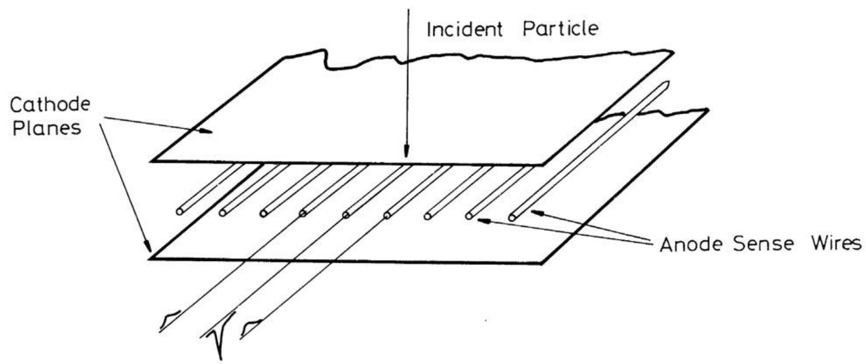


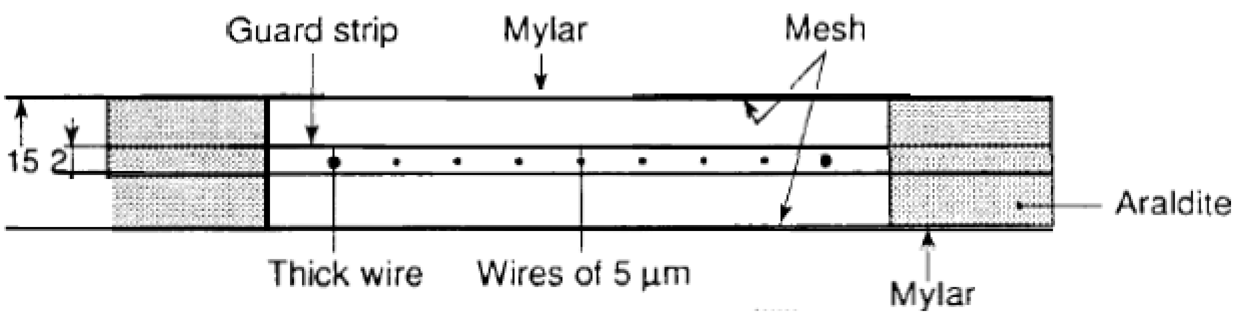
Planar design:
- E uniform and perpendicular to the electrodes
- Amount of ionization produced proportional to path length and to position where the ionization occurs
- Not proportional to energy

Cylindrical proportional counter:
- Single anode wire in a cylindrical cathode
- E~1/r: weak field far from the wire
- Electrons/ions drift in the volume
- Multiplication occurs near the anode

Multi Wire Proportional Chamber

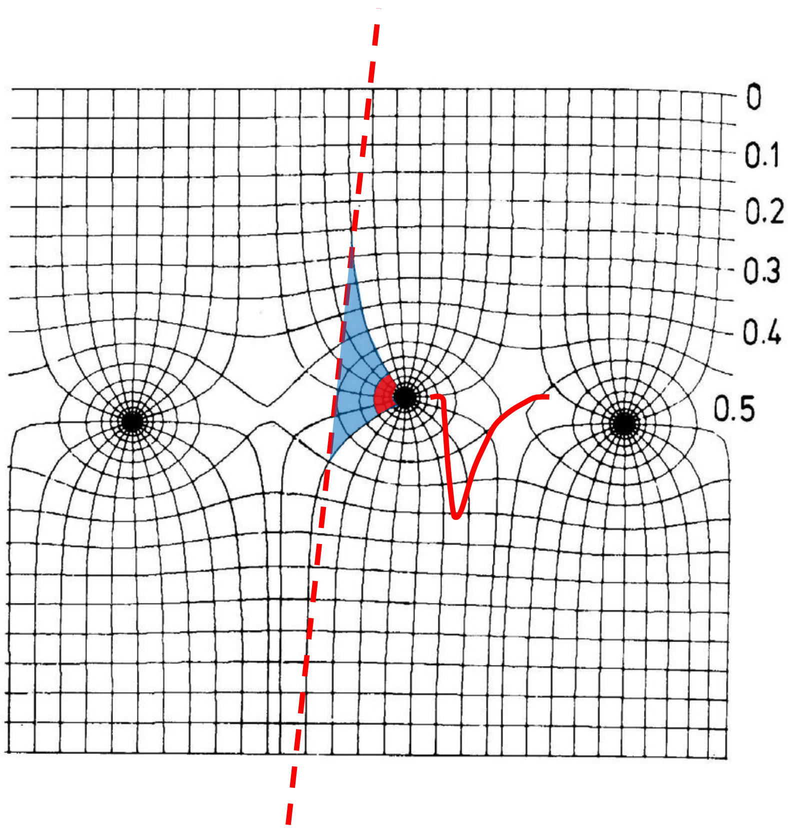
- The detectors presented so far do not give a position measurement of the incident particle
- Solution: Multi-wire proportional chamber (only 1D information though)





Multi Wire Proportional Chamber

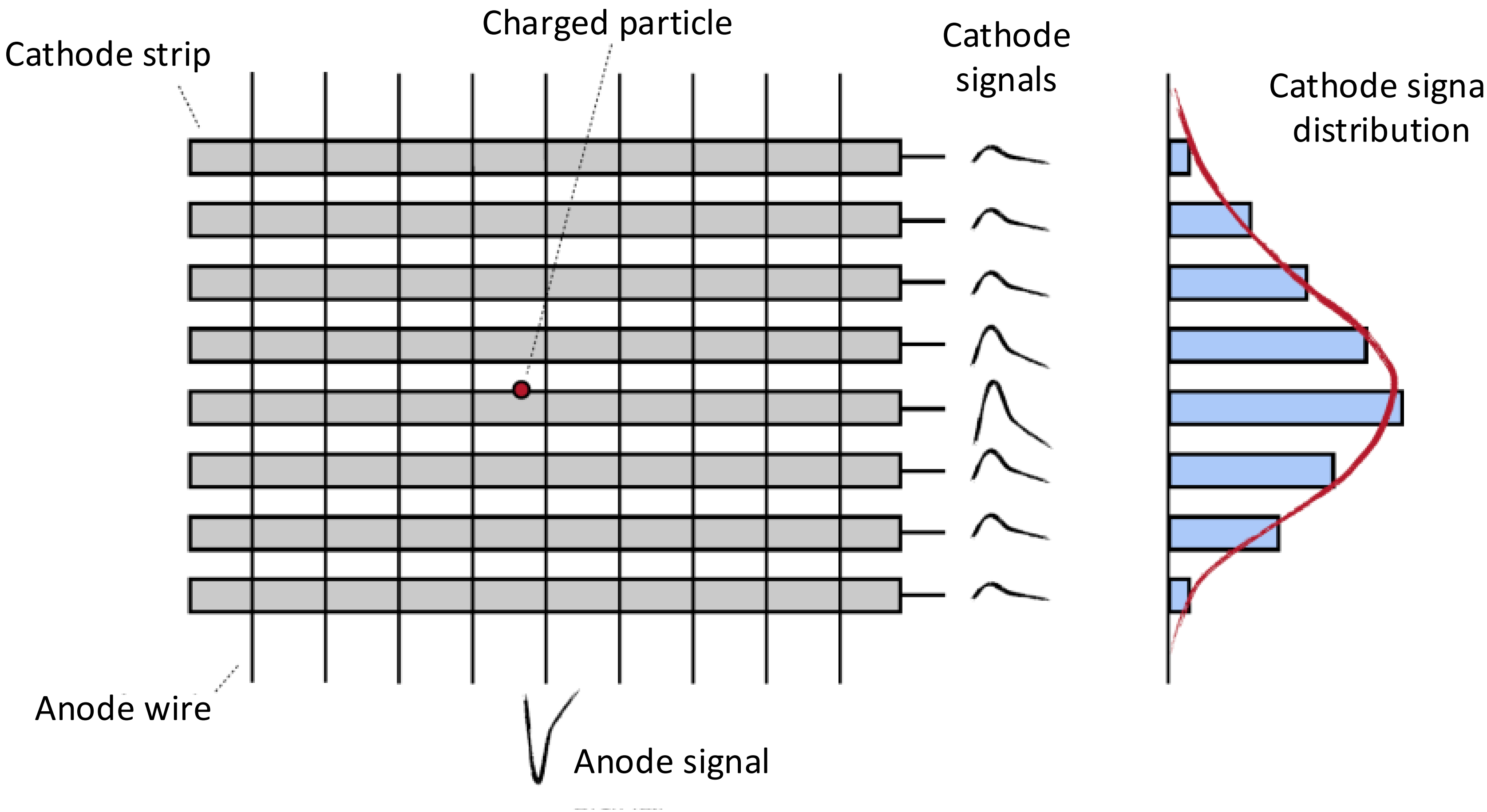
- The detectors presented so far do not give a position measurement of the incident particle
- Solution: Multi-wire proportional chamber (only 1D information though)



- Multiwire proportional chamber with single wire readout
- A charged particle traversing the detector leaves a trail of electrons and ions
- The electrons drift to the wires in the electric field and start to form an avalanche in the high electric field close to the wire
- This induces a signal in the wire which can be readout by an amplifier

Tracking with MWPC

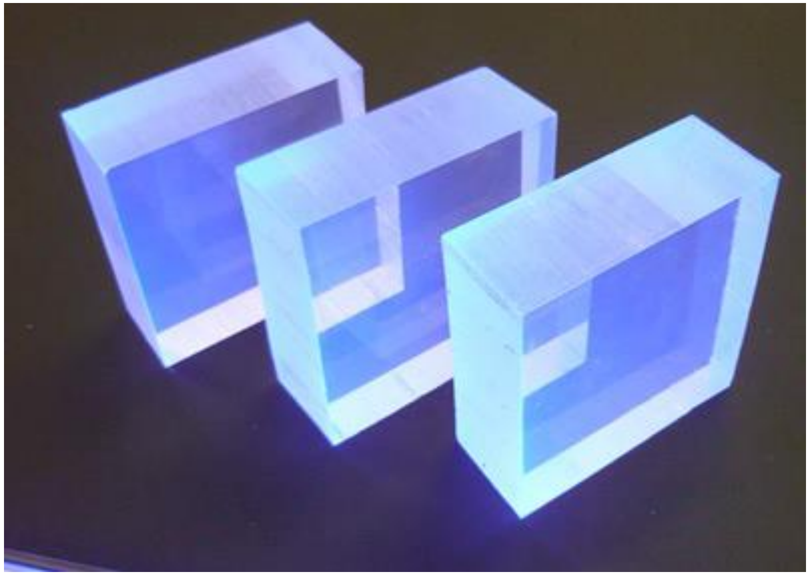
Possible improvements:
- Segmented cathode
- 3-dimension information → Several MWPCs with different orientation

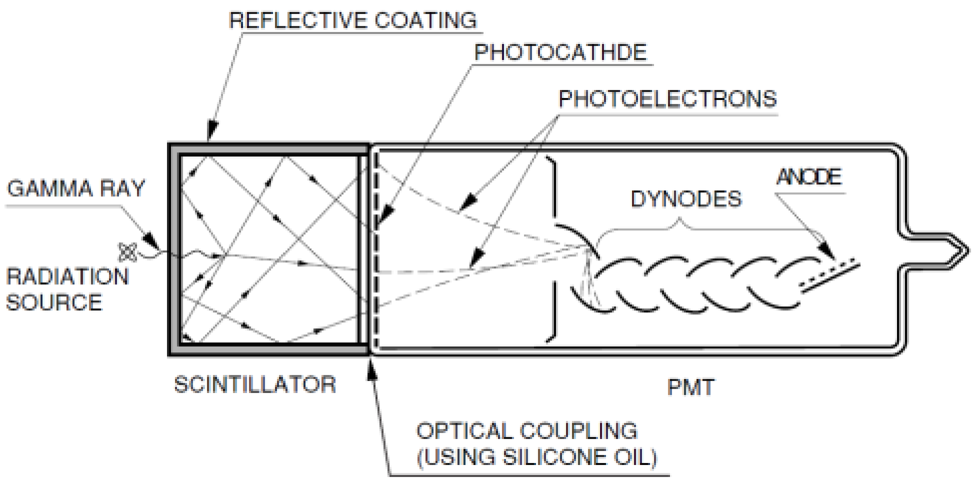


Scintillation Detectors

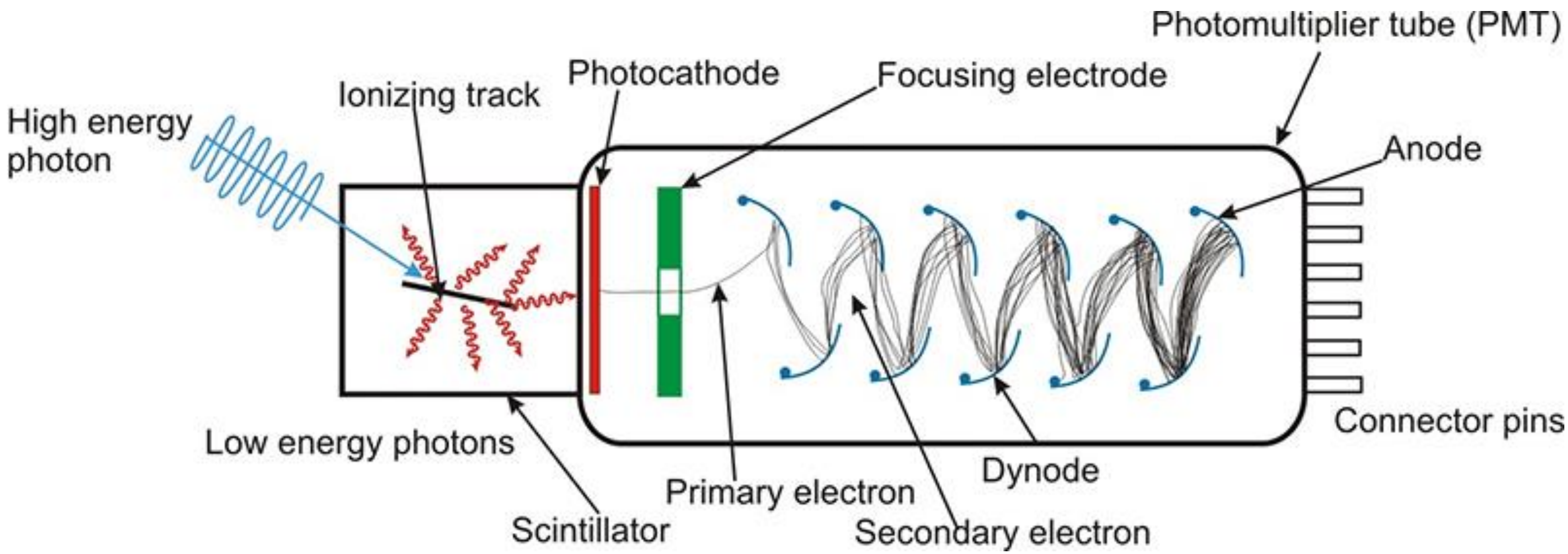
Working Principle

- The detector consists of a chemical compound (organic or inorganic) that emits short light pulses after the molecules of the material have been excited by the passage of a charged particle (dE/dx converted into visible light).
- The light produced is collected via a light guide onto a photodetector.
- Sensitivity to energy and fast time response



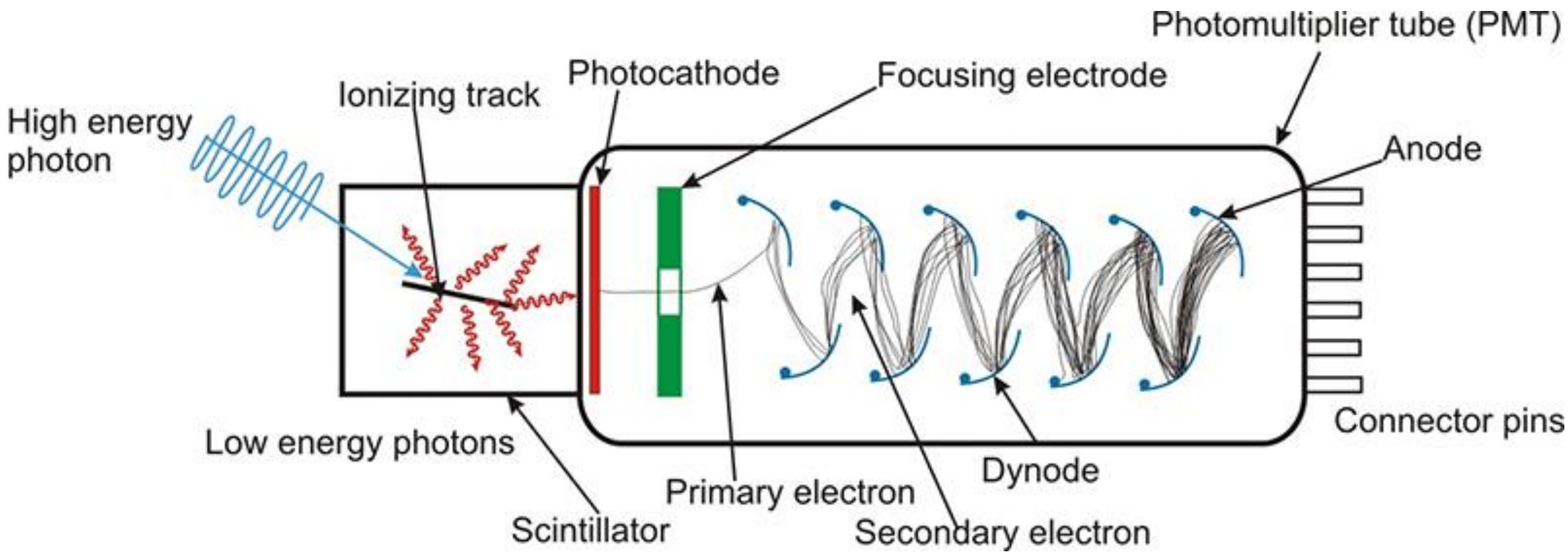


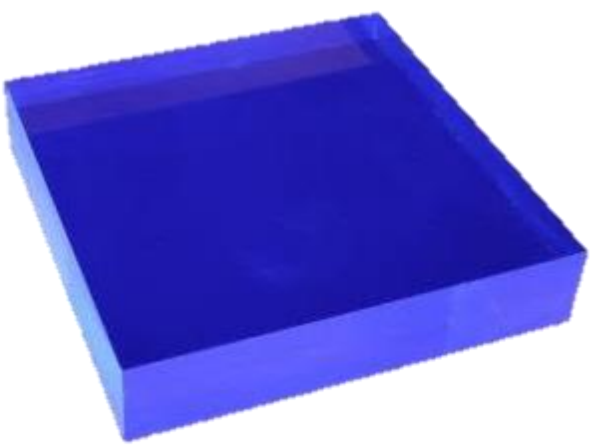
Photomultiplier



- The PMT has a photocathode from which electrons are emitted through the photoelectric effect.
- The electrons are accelerated in the electric field between several subsequent electrodes, dynodes, inside the PMT.
- Due to the increased energies of the electrons, each electron will kick out a number of secondary electrons as they hit the surface of the dynodes.
- With a suitable number of dynodes amplification is obtained before an electric signal is read out at the anode of the PMT.

Photomultiplier





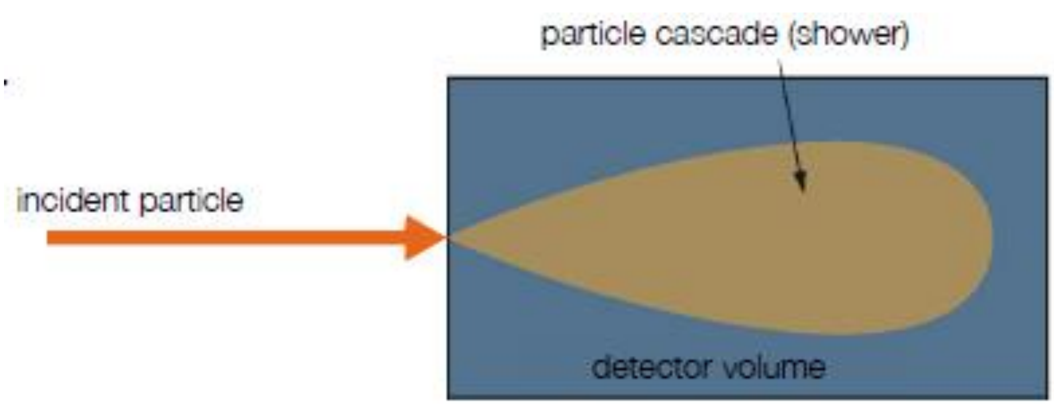
Electromagnetic Calorimeters

Calorimeters

... where most of the particles end their journey...

Calorimetric methods imply total absorption of the particle energy in a bulk of material followed by the measurement of the deposited energy.

Photons, electrons and hadrons interact with media producing secondary particles which leads to a shower development. Thus calorimeters are most widely used in high energy physics to detect the electromagnetic (electromagnetic calorimeters) and hadronic (hadron calorimeters) showers.

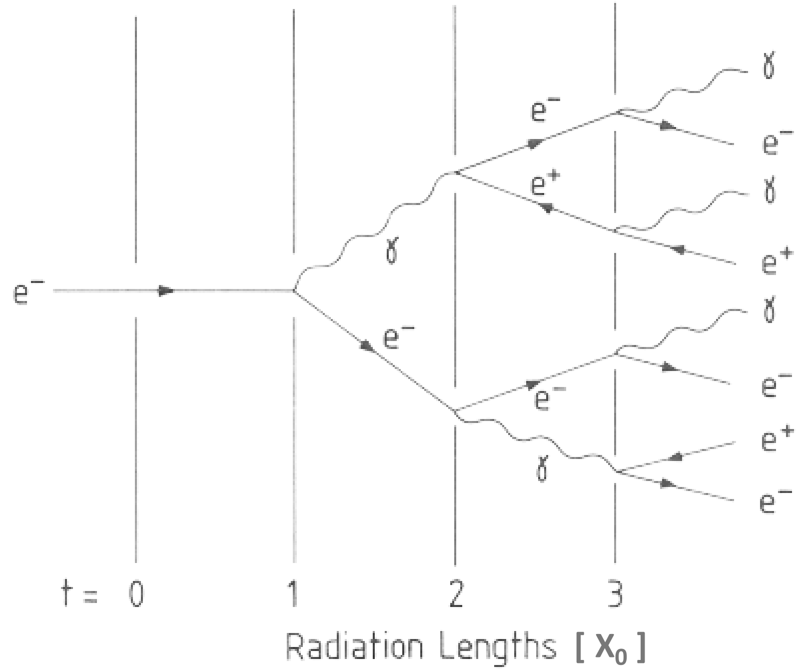


Analytic Shower Model

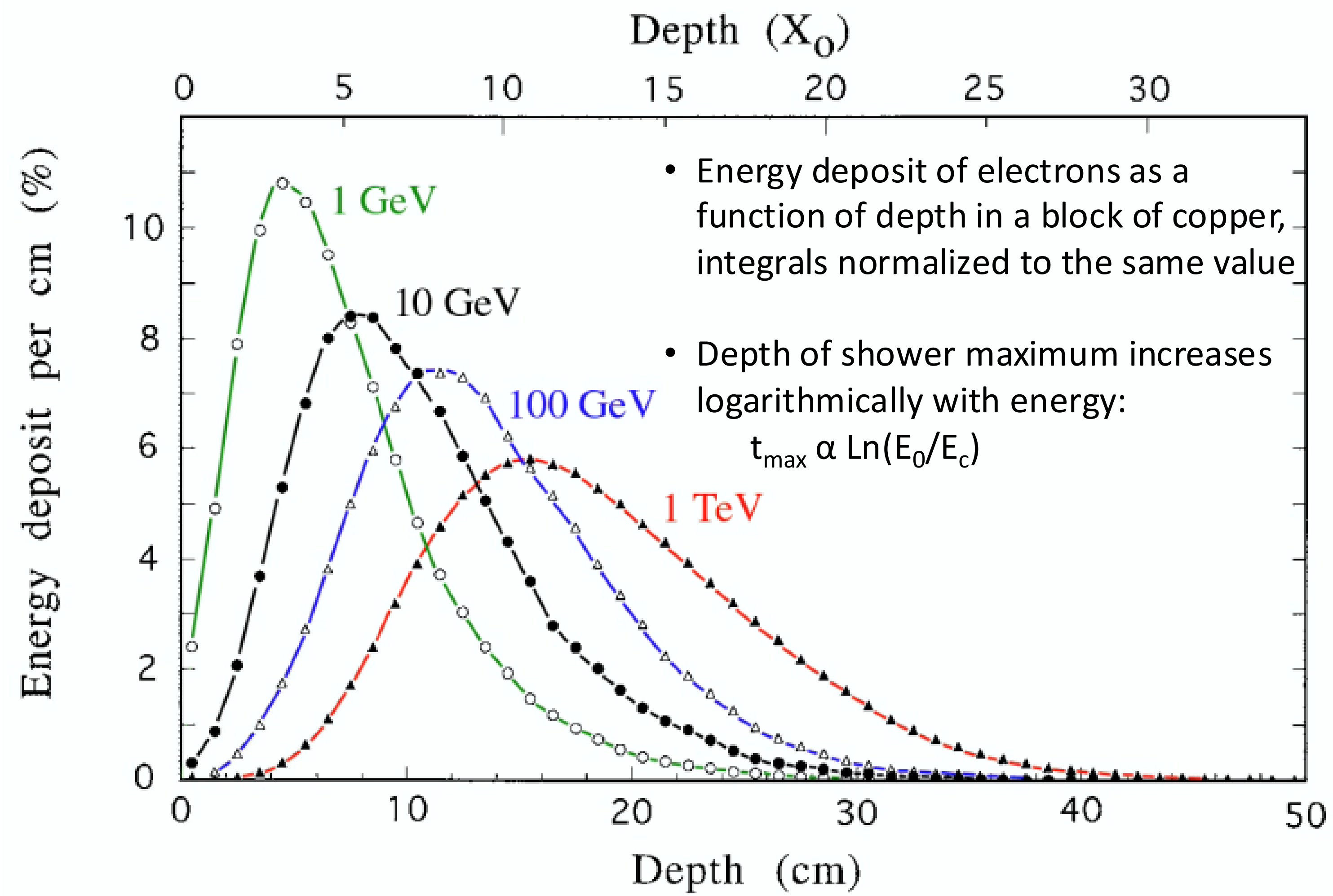
ε(t) Fracc. Incident E	1	1/2	1/4	1/8	...
N(t) Number of cascades	1	2	4	8	...

Simplified shower model (Heitler):

- Shower development is governed by X_0
- Depth of the shower $t = x/X_0$
- Particles after t: $N(t) = 2^t$
- Each with energy $E(t) = E_0/N(t) = E_0/2^t$
- Shower stops if $E < E_c$
- Number of particles $N = E/E_c$
- Maximum at $t_{max} \propto Ln(E_0/E_c)$



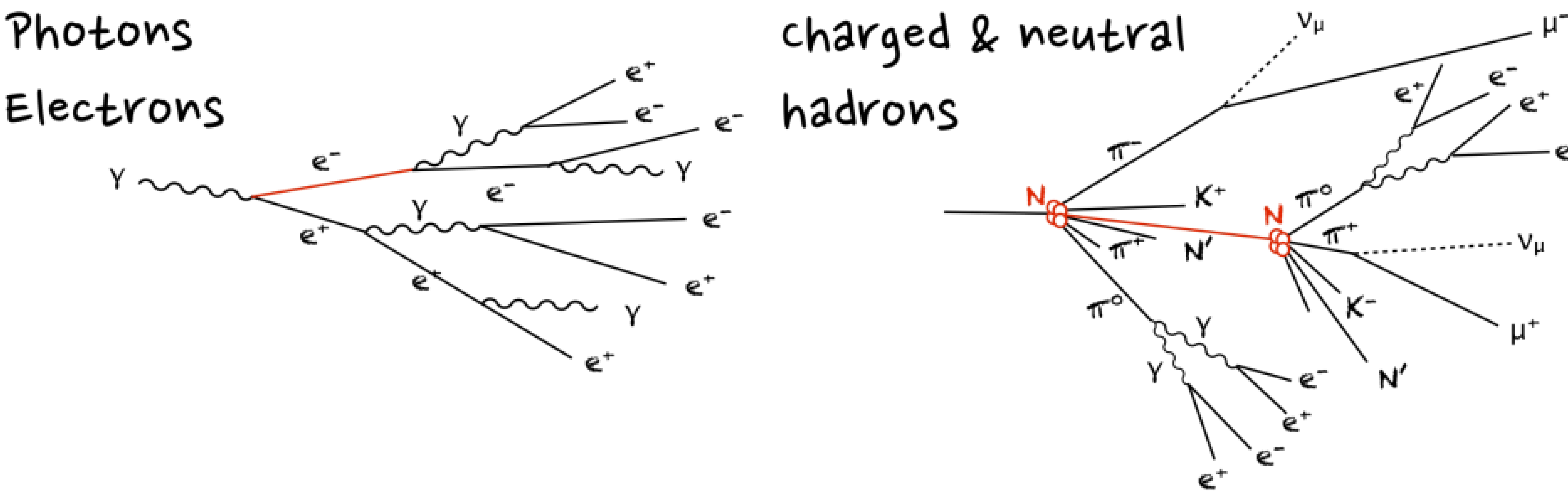
Longitudinal Shower Shape



- Energy deposit of electrons as a function of depth in a block of copper, integrals normalized to the same value
- Depth of shower maximum increases logarithmically with energy:

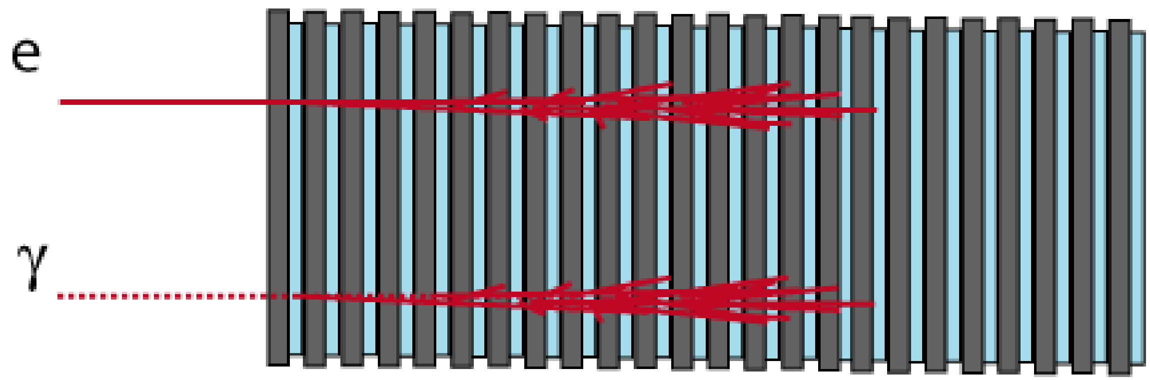
  $t_{max} \propto Ln(E_0/E_c)$

Hadronic Shower



- Ionization energy of charged particles
- Neutrons
- e.m. Showers
- Photons from nuclear de-excitation
- Non detectable energy

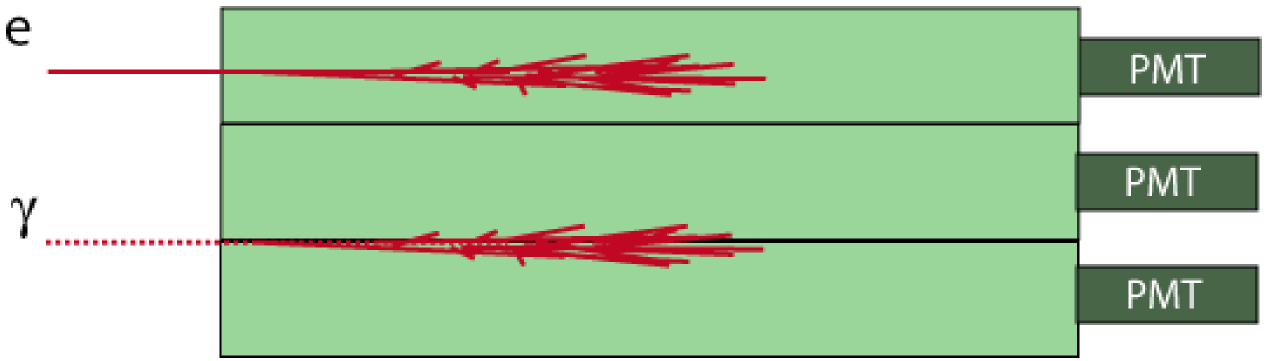
Sampling and Homogeneous Calorimeters



Sampling calorimeter
Alternating layers of absorber and active material

Homogeneous calorimeter
The active material y the absorber itself

Homogeneous calorimeter

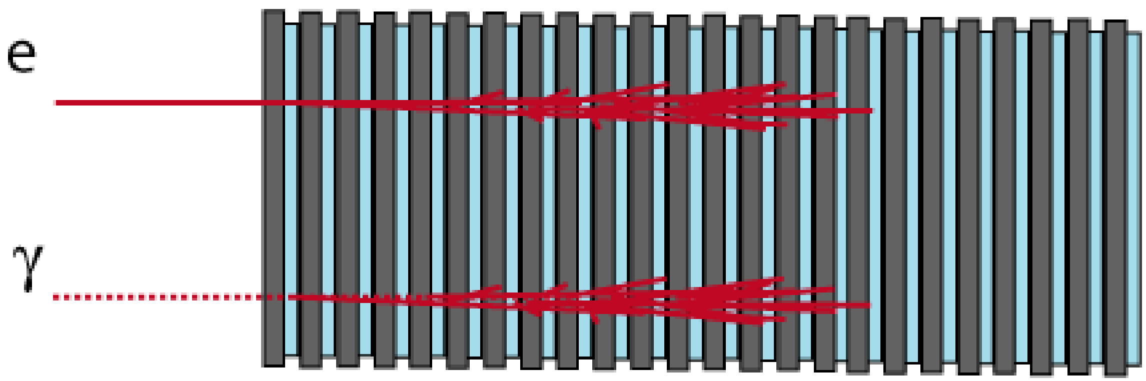


Homogeneous calorimeter
The active material y the absorber itself

- Advantage: Optimal energy resolution, same response everywhere (good linearity), see all particles in the shower (best statistical precision)
- Disadvantage: Expensive and limited granularity

Homogeneous calorimeters are exclusively used for electromagnetic calorimeters (electrons, positrons and photons)

Sampling calorimeter



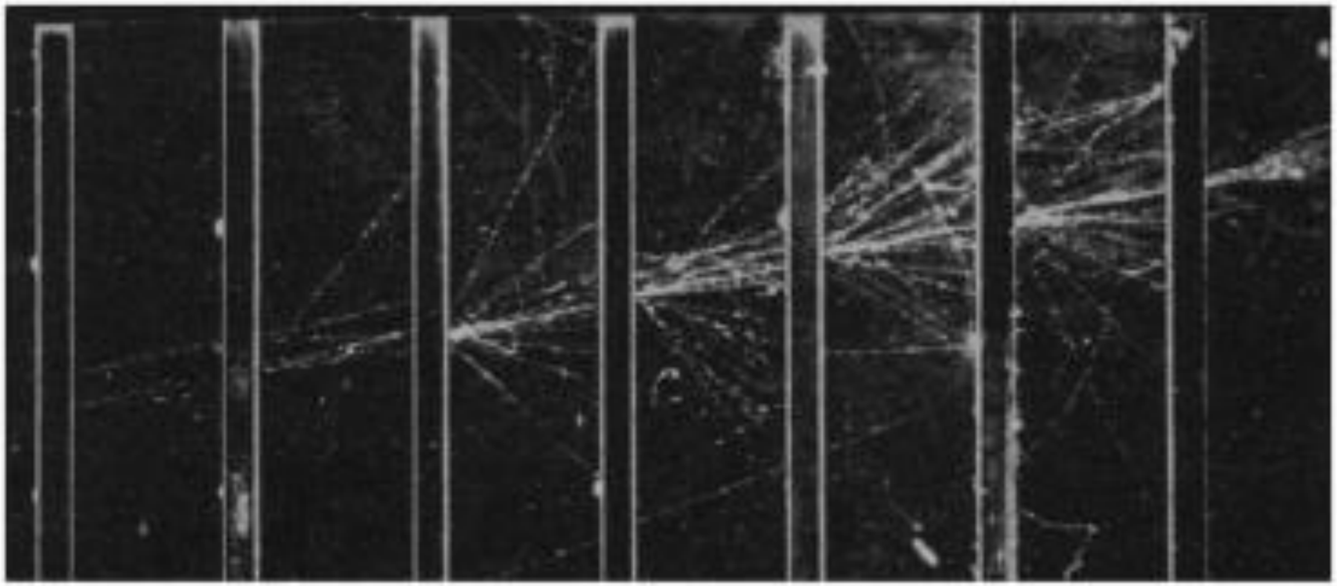
Sampling calorimeter
Alternating layers of absorber and active material

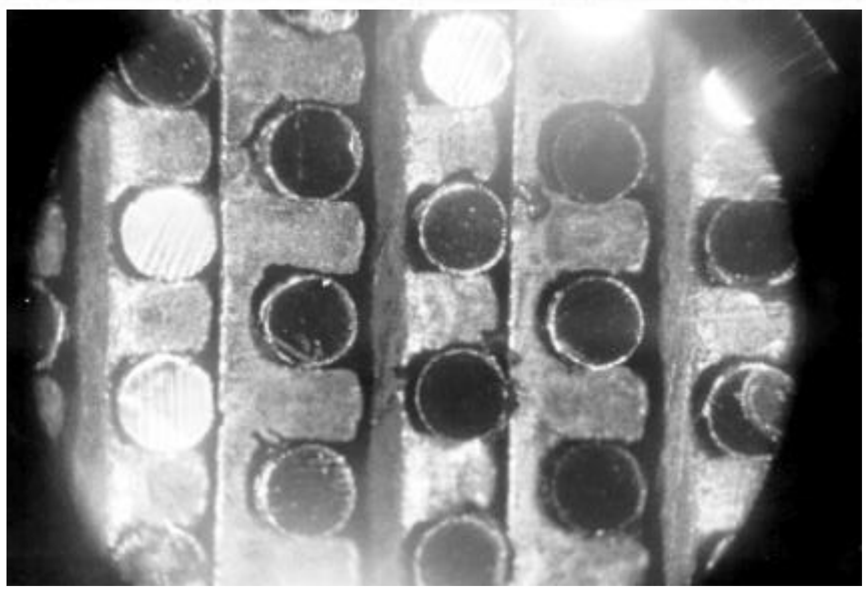
- Advantage: Better optimization for the corresponding requirements. Very compact. Simpler and cheaper than homogeneous.

- Disadvantages: Reduced energy resolution due to sampling fluctuations

Homogeneous Calorimeter

Sampling Calorimeter

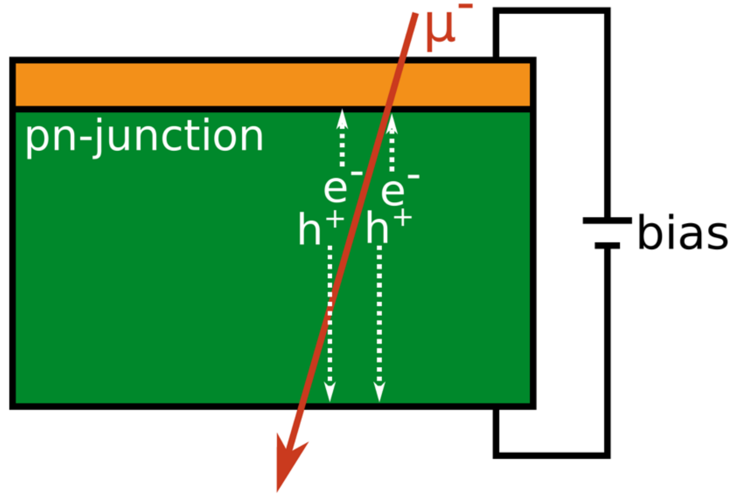


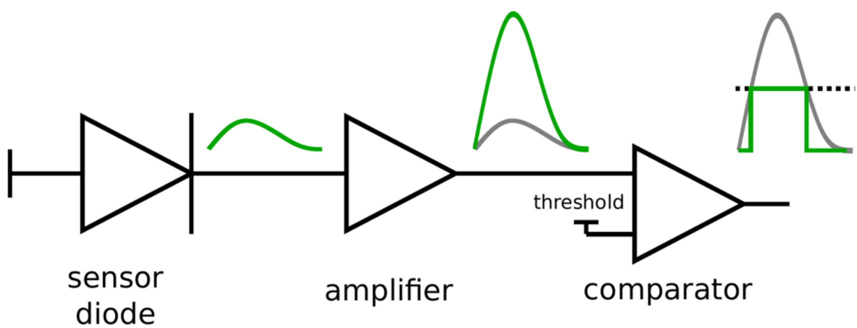


H1 Spaghetti calo

Silicon Detectors

- The working principle is like the gaseous systems
- Simplest detector: pn-junction
  - Operated in reverse bias → Depletion region
  - Traversing particle → Ionization = signal carriers
  - Typical thickness 50 – 300 µm
- Shockley-Ramo Theorem:
  Moving charges induce signal on electrode

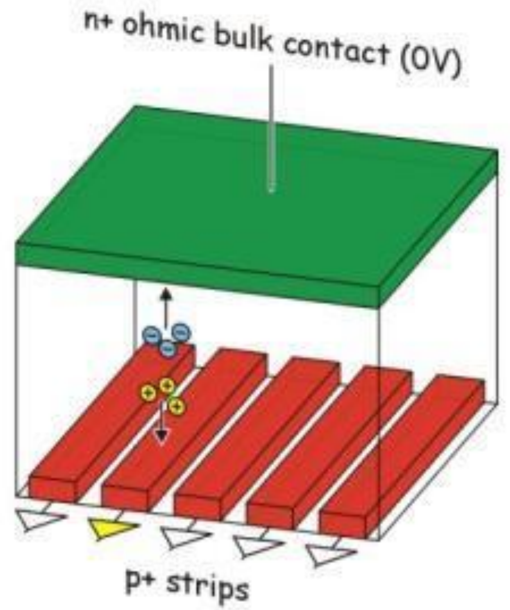




Increasing the Resolution: Segmentation

- **Silicon strip detectors**

A strip detector is an arrangement of strip like shaped implants acting as charge collecting electrodes (one-dimensional array of diodes).



- Double sided silicon strip detectors

Two dimensional position measurements can be achieved by applying an additional strip like doping on the wafer backside by use of a double sided technology.

- Pixel detectors

2D array of pixels. Each pixel = 1 pn-junction
True 2 dimensional information without ambiguities

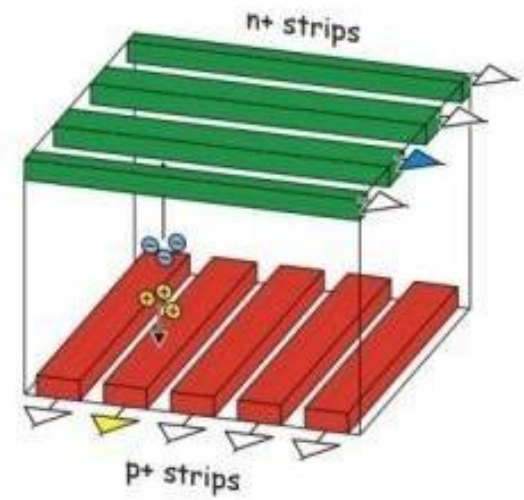
Increasing the Resolution: Segmentation

- Silicon strip detectors

A strip detector is an arrangement of strip like shaped implants acting as charge collecting electrodes (one-dimensional array of diodes).

- **Double sided silicon strip detectors**

Two dimensional position measurements can be achieved by applying an additional strip like doping on the wafer backside by use of a double sided technology.



- Pixel detectors

2D array of pixels. Each pixel = 1 pn-junction
True 2 dimensional information without ambiguities

Increasing the Resolution: Segmentation

- Silicon strip detectors

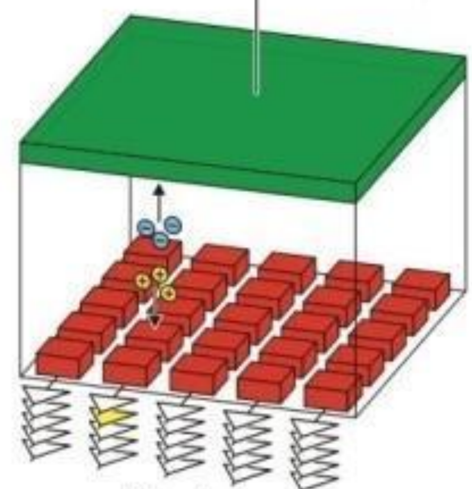
A strip detector is an arrangement of strip like shaped implants acting as charge collecting electrodes (one-dimensional array of diodes).

- Double sided silicon strip detectors

Two dimensional position measurements can be achieved by applying an additional strip like doping on the wafer backside by use of a double sided technology.

- **Pixel detectors**

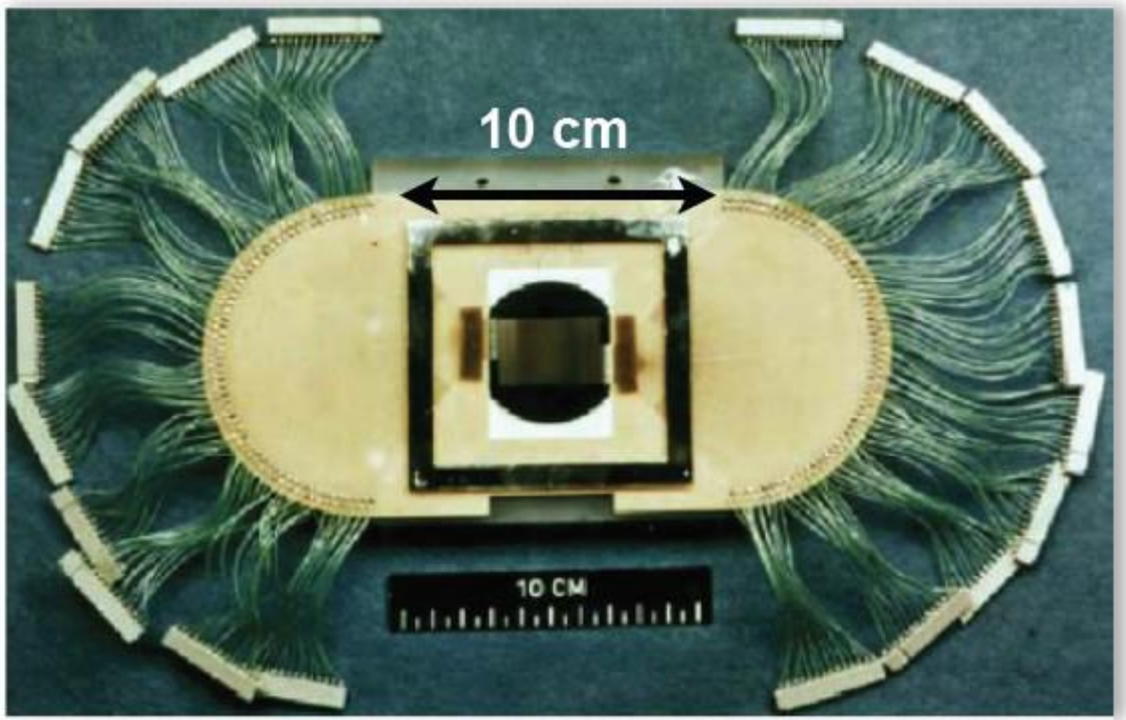
2D array of pixels. Each pixel = 1 pn-junction
True 2 dimensional information without ambiguities



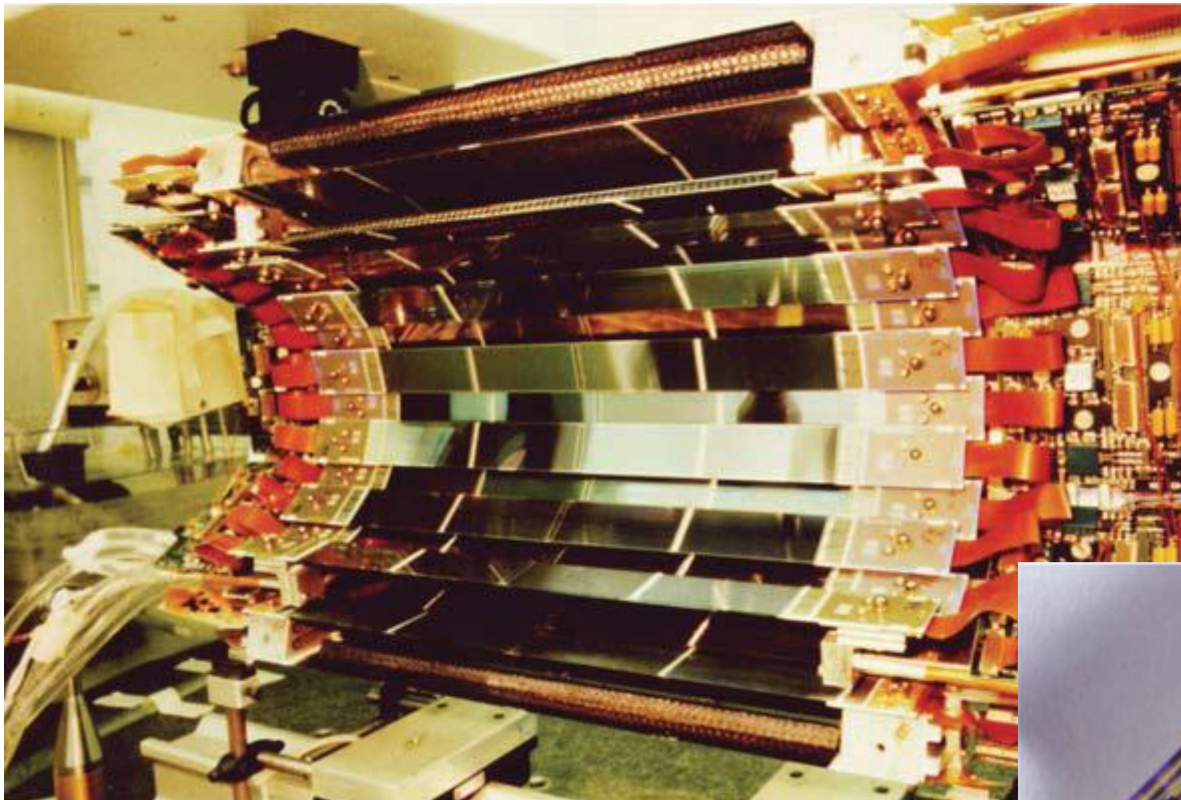
NA-11 (End Date 1988)

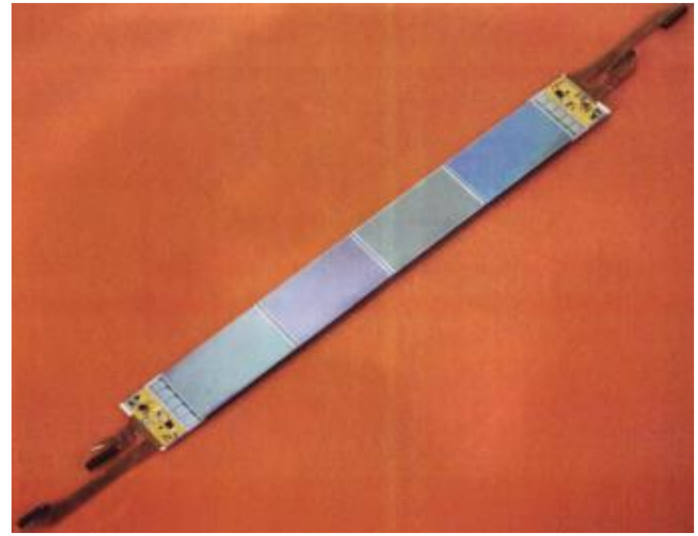
First use of a position-sensitive silicon detector in HEP experiment

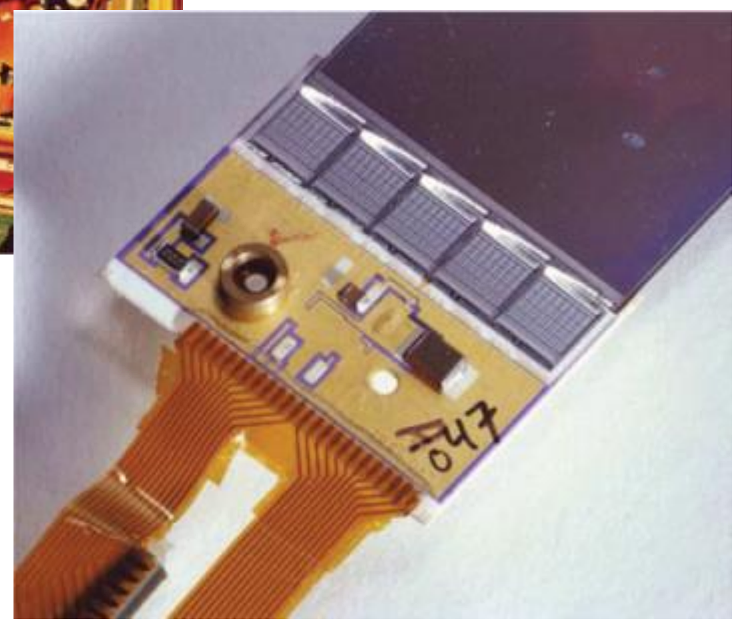
- Measurement of charm-quark lifetime
- 1200 diode strips on 24 x 36 mm^2 active area
- 250-500 μm thick bulk material
- 4.5 μm resolution



DELPHI MicroVertex (End Date 2000)

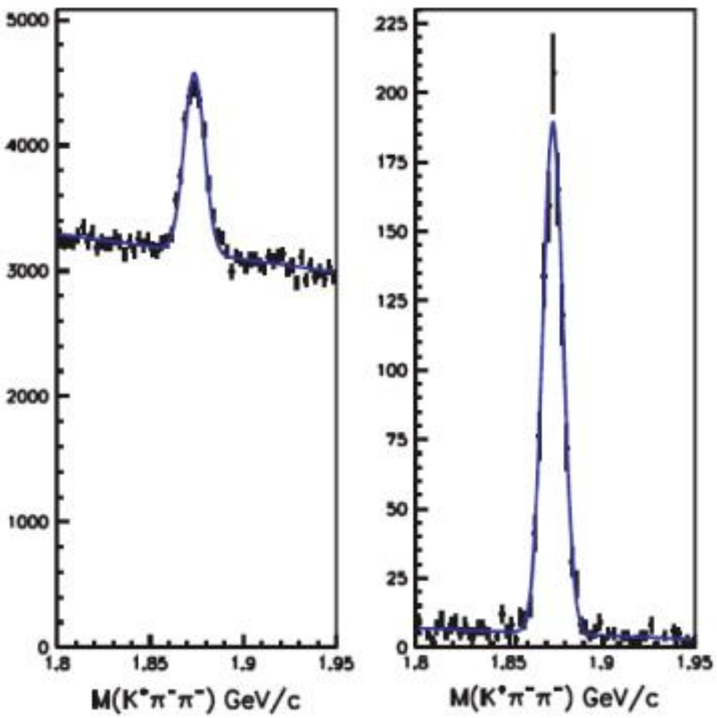


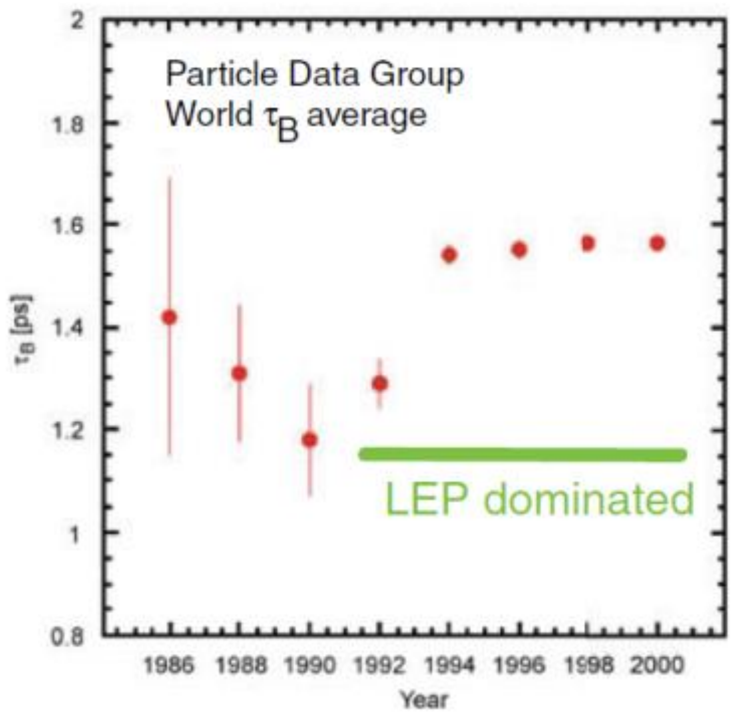




- A silicon ladder R/O electronics at the end
- 300 µm DSSD, 2 layers, 40 cm long
- No extra material in the sensitive area

Physics Improvements

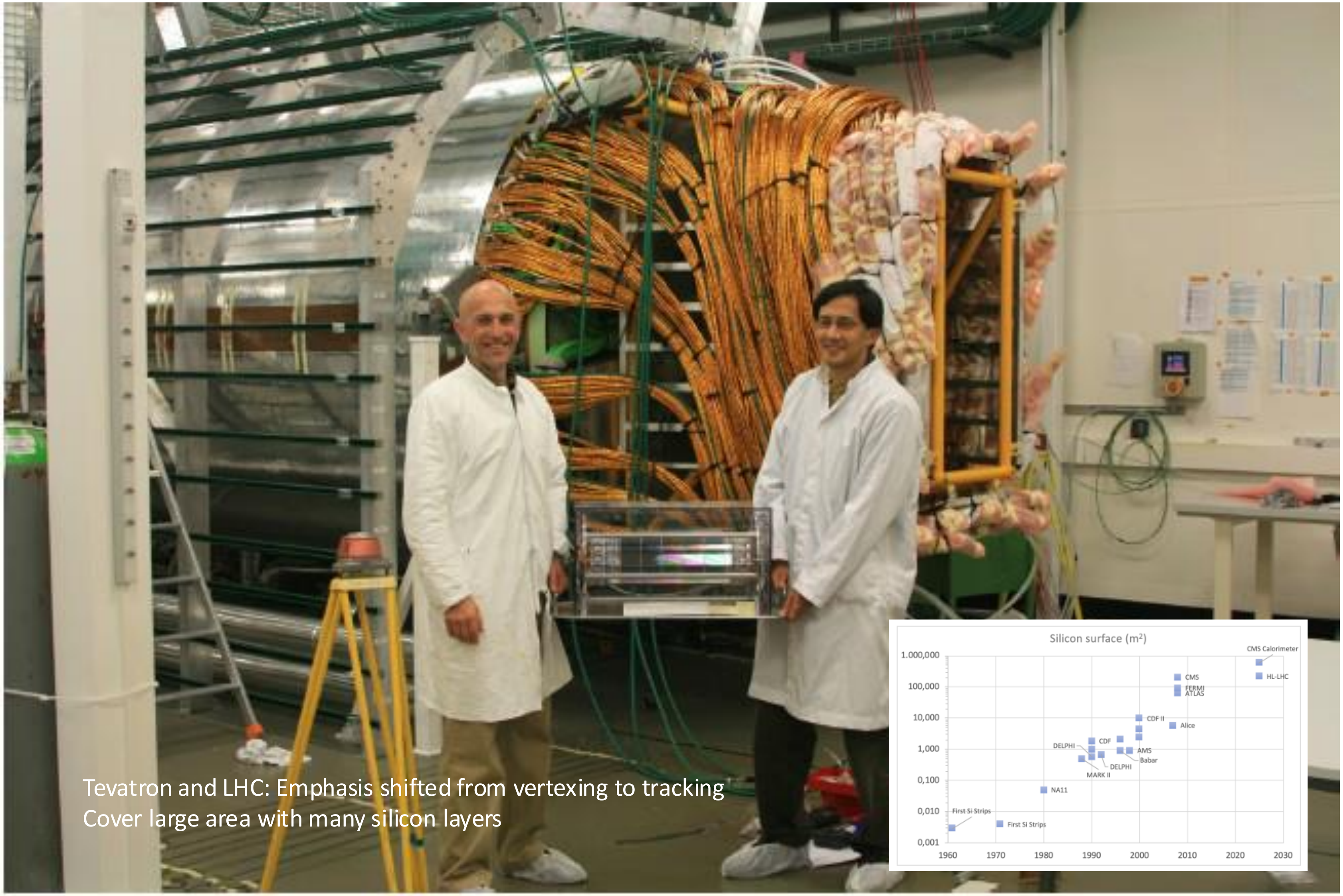




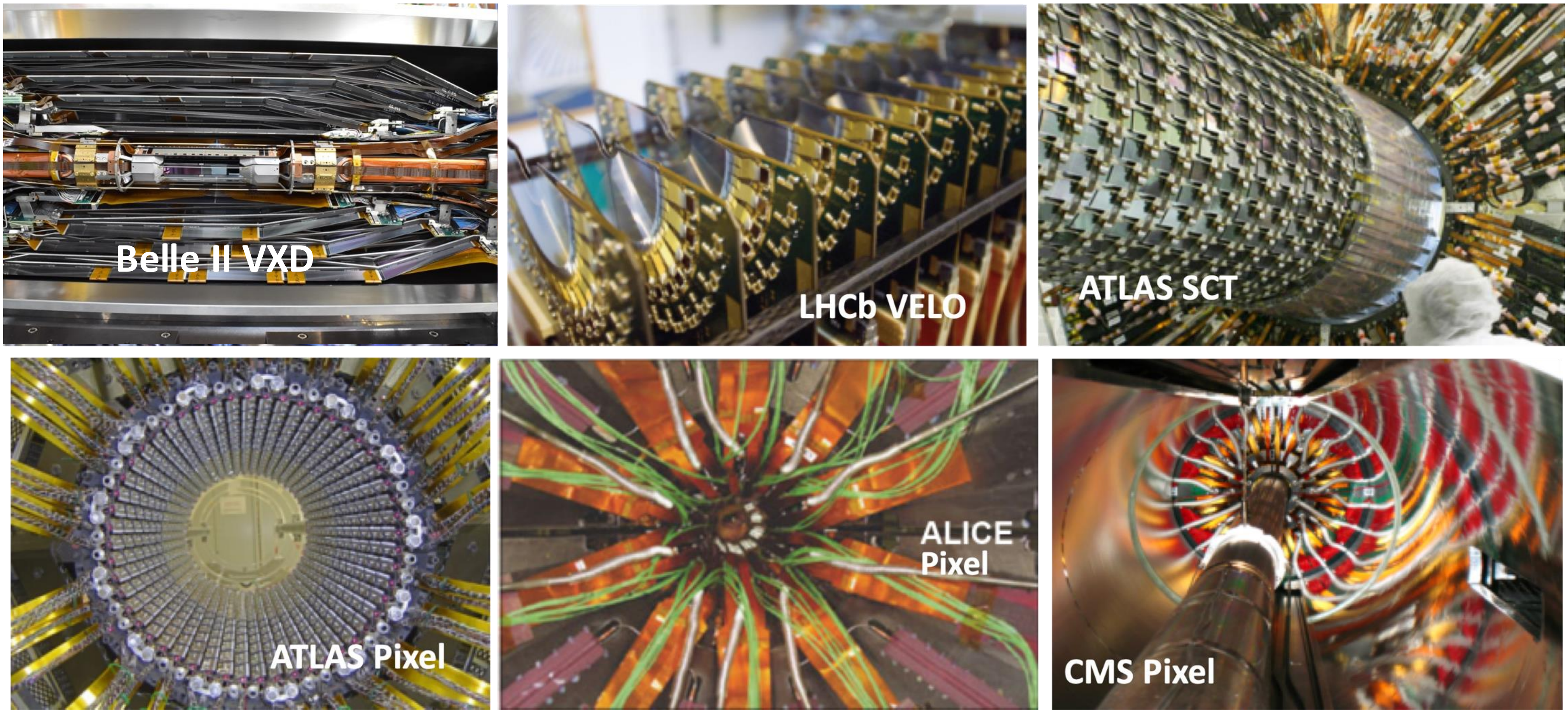
- $D^{\pm} \to K\pi\pi$ mass peaks before and after background removal using vertex cut at CDF
- 3 Si layers from 1.5 cm to 29 cm

- B lifetime measurements
- Silicon detector developments in the 90s

DELPHI vs CMS



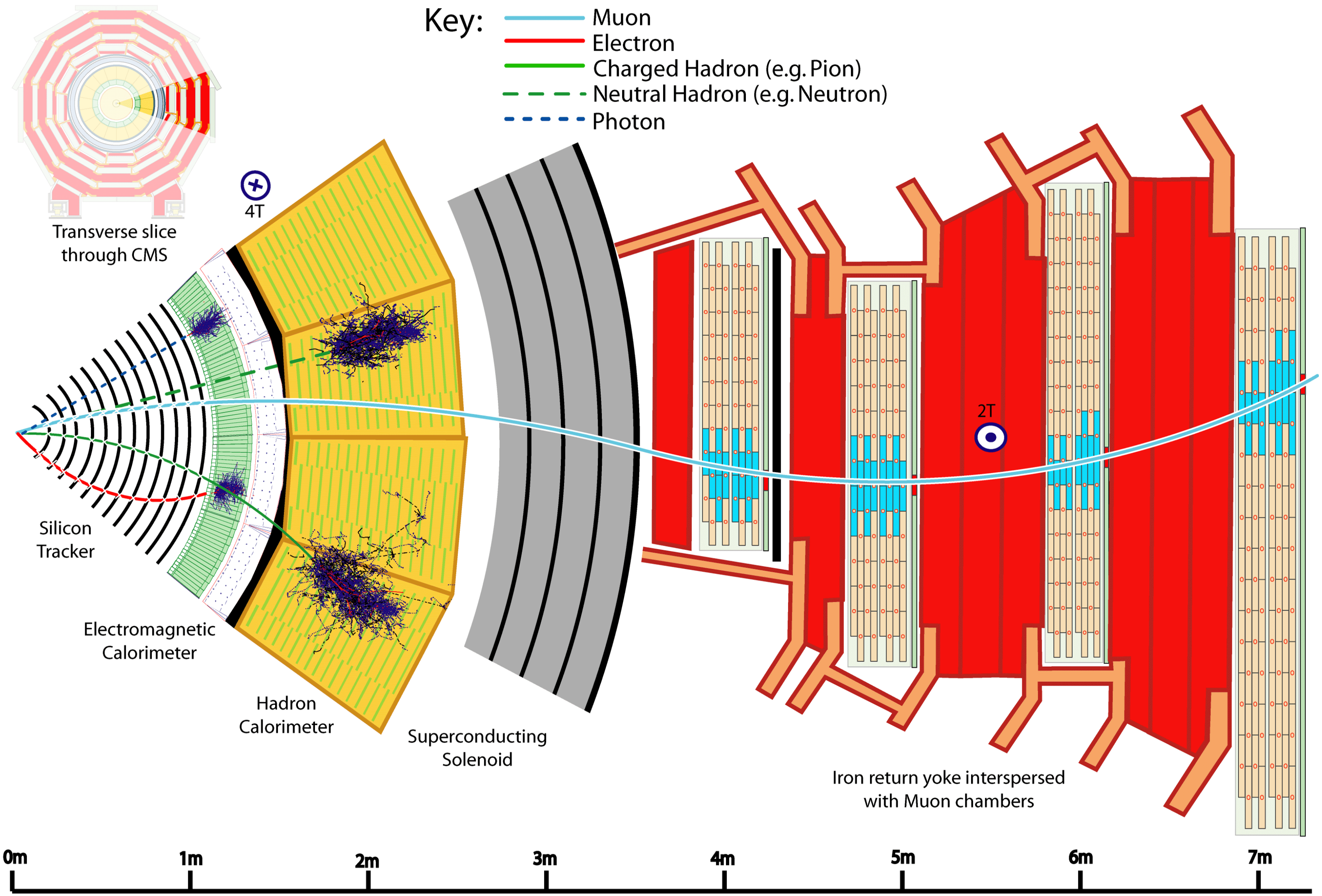
Nowadays: Silicon Everywhere



Summary

- Detectors are ***the*** instrument in nuclear and particle physics
- Detectors are extremely complex systems, needing joint development efforts of instrumentation physicist and engineers in large collaborations
- Constant activity and evolution, pushing the boundaries of commercial technologies and expanding to many applications in other fields

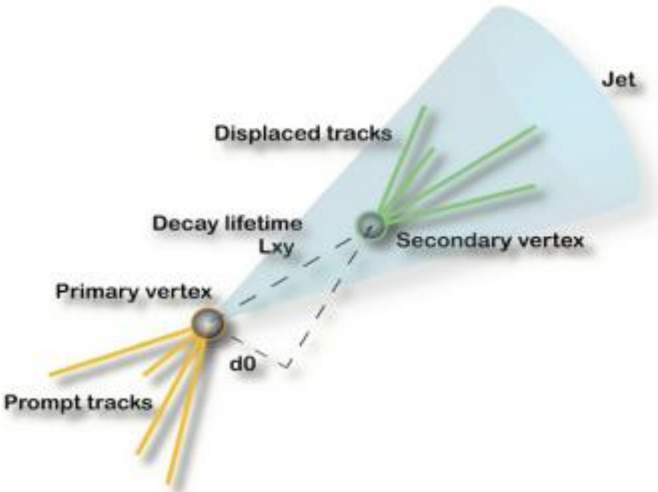
Summary



Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

Thank you

Vertexing Requirements HEP

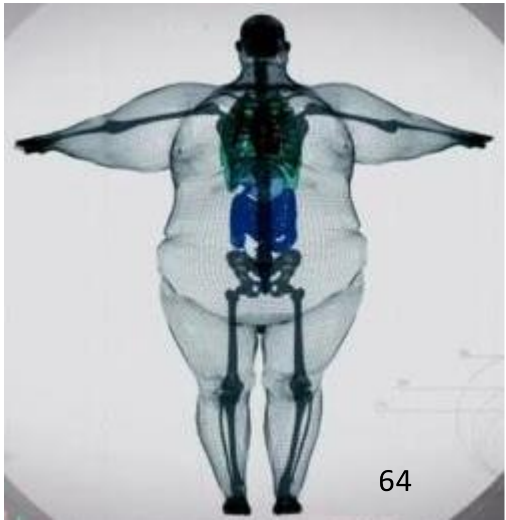


$$\sigma_{d0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2-r_1)^2}} \oplus \frac{r}{p\sin^{\frac{3}{2}}\theta} 13.6MeV\sqrt{\frac{x}{X_0}}$$

$$\sigma_{d0} \approx a \oplus \frac{b}{p\sin^{\frac{3}{2}}\theta}$$

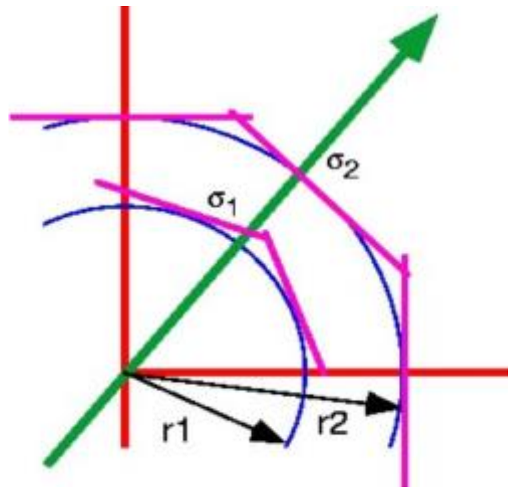
	a (μm)	b (μm GeV)
LHC	12	70
STAR	12	19
Belle II	8.5	10
ILC	5	10

- Common vertex detector requirements
  - First layer close to the IP
  - Low material budget
    - Reduced services
    - Low power dissipation
  - High granularity
    - Good spatial resolution
  - Fast readout
  - Radiation hardness



a: Governs high momentum
b: Dominates at low momentum

Vertexing Requirements HEP

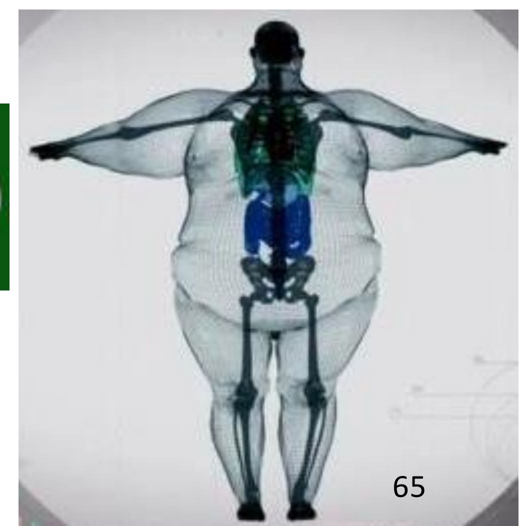


$$\sigma_{d0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{\frac{3}{2}}\theta} 13.6MeV\sqrt{\frac{x}{X_0}}$$

$$\sigma_{d0} \approx a \oplus \frac{b}{p\sin^{\frac{3}{2}}\theta}$$

	a (µm)	b (µm GeV)
LHC	12	70
STAR	12	19
Belle II	8.5	10
ILC	5	10

- Common vertex detector requirements
  - First layer close to the IP
  - Low material budget
    - Reduced services
    - Low power dissipation
  - High granularity
    - Good spatial resolution
  - Fast readout
  - Radiation hardness



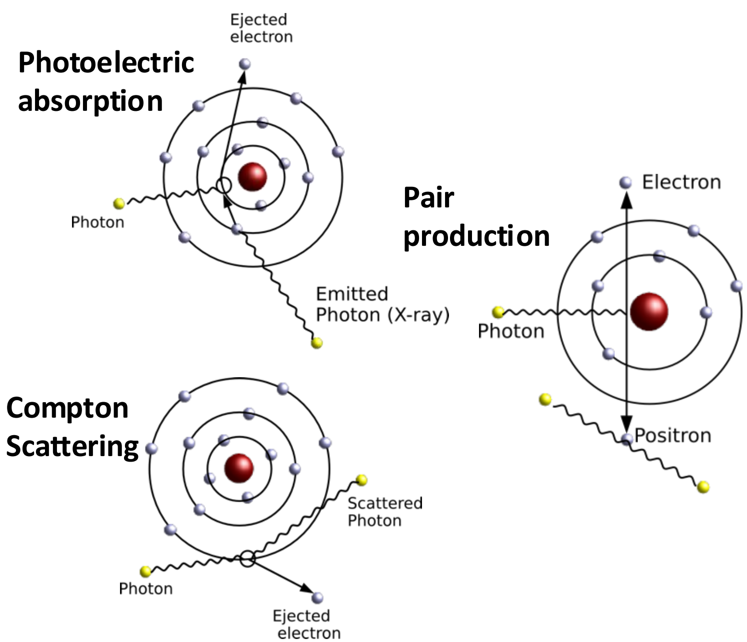
a: Governs high momentum
b: Dominates at low momentum

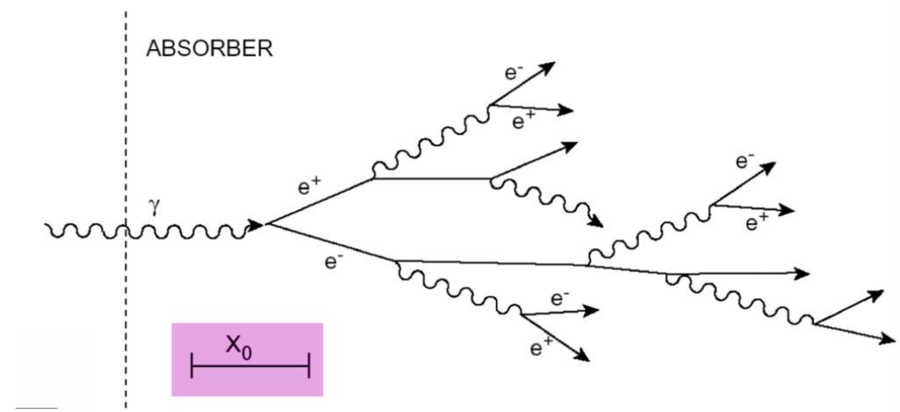
Neutrals (Photons)

We can't detect neutral particles directly.

We can, though, detect the charged particles that they produce while interacting with the detector material.

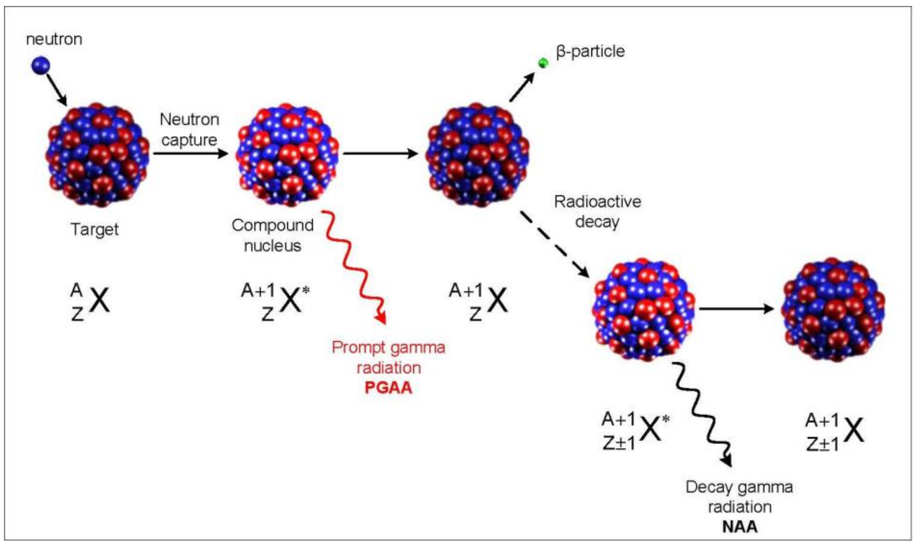
Photons: They produce electrons and photons in their interactions, producing e.m. cascades if the energy is high enough



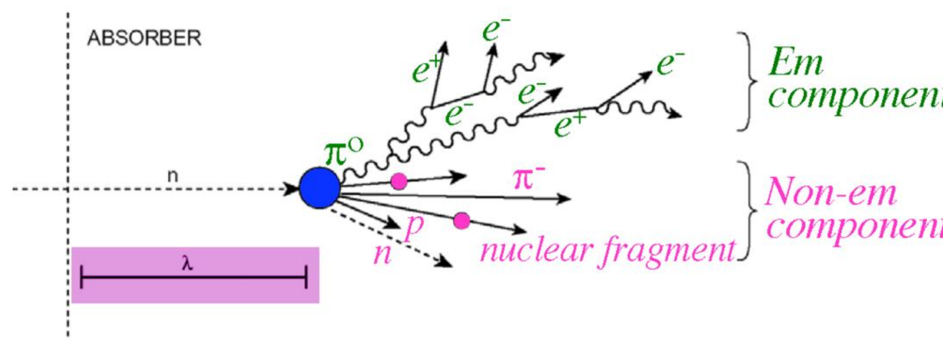


Neutrons

As with photons, we see the producto of their interaction with the detector material or with the media we place to force the interaction.



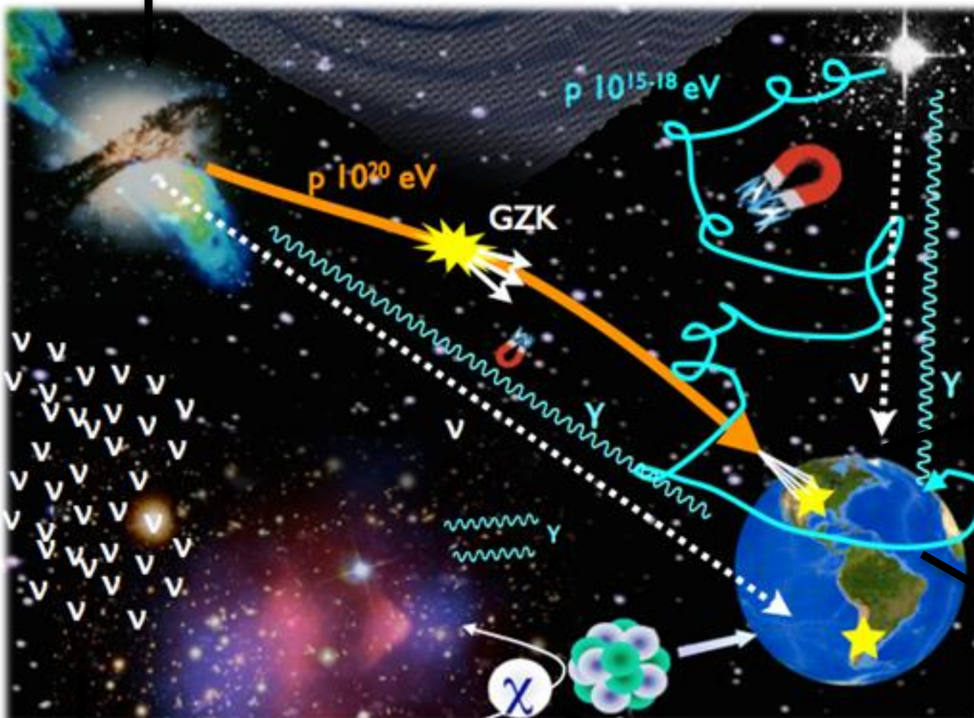
Hadronic shower



Cosmic Accelerators

Cosmology and Dark Energy

Astroparticles



Gamma-ray astronomy

Neutrino astronomy

Cosmic rays

Neutrino experiments

Dark matter