

The Physics of Particle Detectors

Lecture Notes

SS 2012

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Outline of the course

- Introduction to HEP detectors
 - Interaction of Particles with Matter
 - Gaseous detectors
 - Scintillators detectors
 - Solid state detectors
 - Introduction to Synchrotron Radiation detectors
 - Readout Electronics
 - Vertex and Tracking
 - Calorimetry (electrons and photons)
 - Calorimetry (charged hadrons and neutrons)
 - Particle Identification
 - Detector systems
- } Detection principles / materials
- } Measurements of specific particle observables

History of instrumentation

1906: Geiger Counter, H. Geiger, E. Rutherford

1910: Cloud Chamber, C.T.R. Wilson

1912: Tip Counter, H. Geiger

1928: Geiger-Müller Counter, W. Müller

1929: Coincidence Method, W. Bothe

1930: Emulsion, M. Blau

1940-1950: Scintillator, Photomultiplier

1952: Bubble Chamber, D. Glaser

1962: Spark Chamber

1968: Multi Wire Proportional Chamber, C. Charpak

1970es: Silicon era

Etc. etc. etc.

On tools and instrumentation

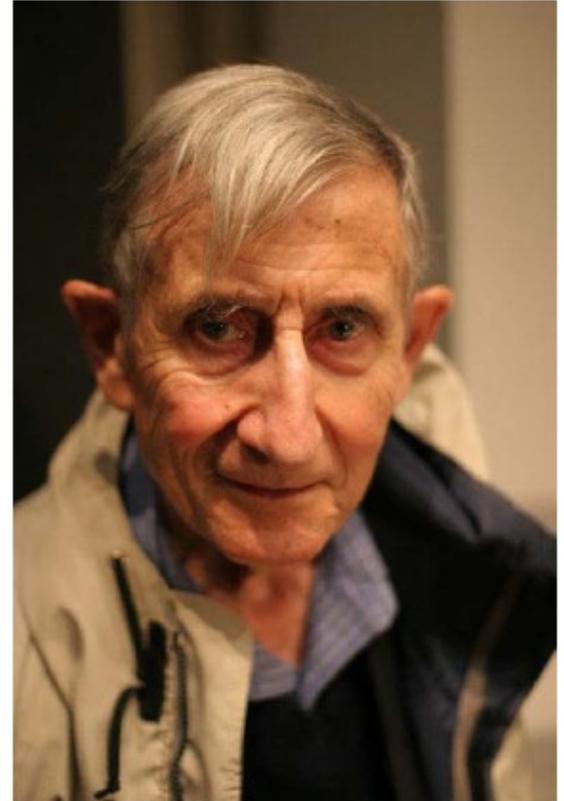
“New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained”

Freeman Dyson (quantum electrodynamics)

➔ New tools and technologies will be extremely important to go beyond LHC



Nobel prices for instrumentation

1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron & Discoveries

1948: P.M.S. Blacket, Cloud Chamber & Discoveries

1950: C. Powell, Photographic Method & Discoveries

1954: Walter Bothe, Coincidence method & Discoveries

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries

1992: Georges Charpak, Multi Wire Proportional Chamber

Preliminary definition

The Physics of Particle Detectors

What is a **P**article?

What is a **D**etector?

How to detect a particle?

What is a Particle?

The theoretician answer:

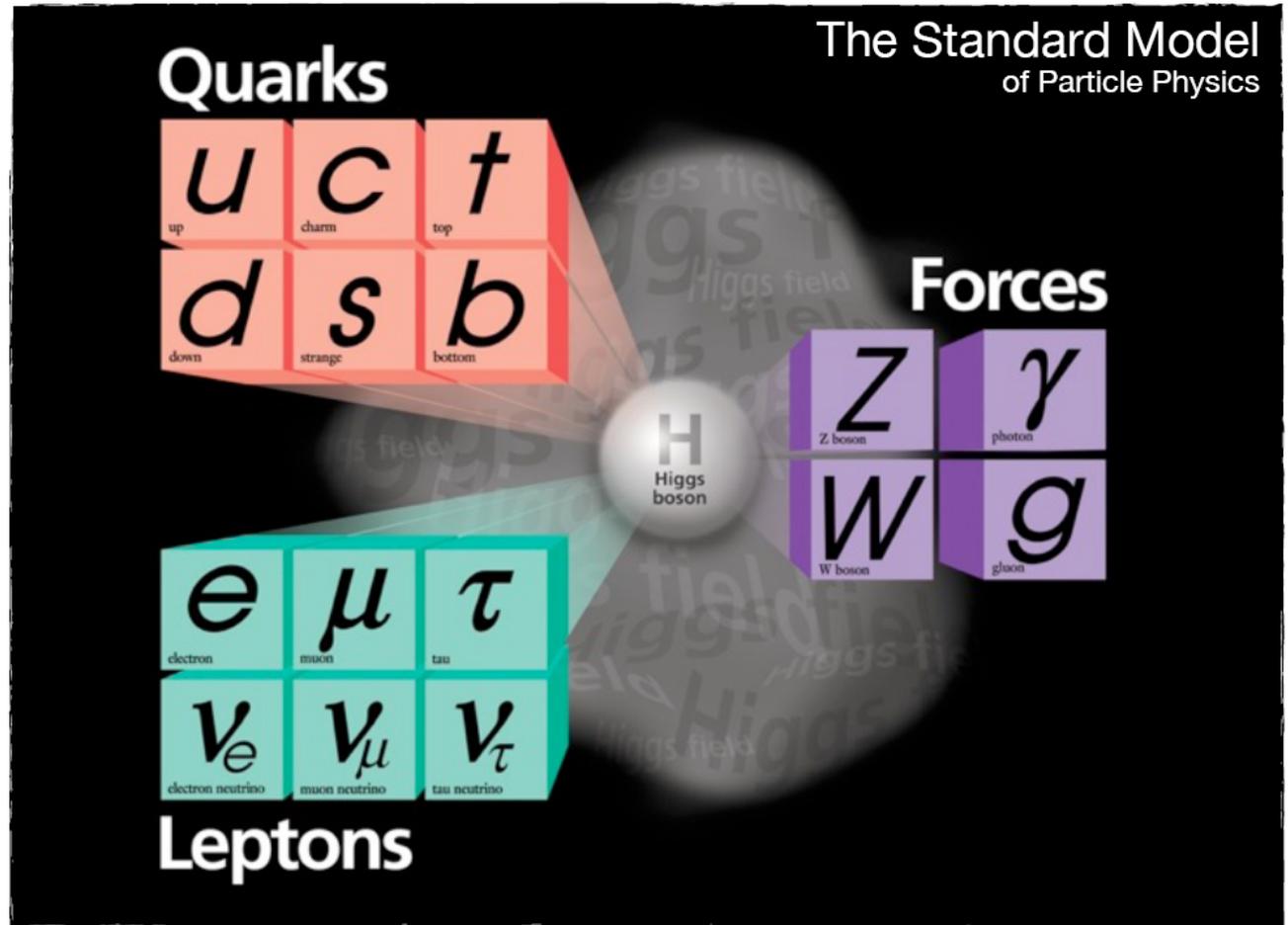
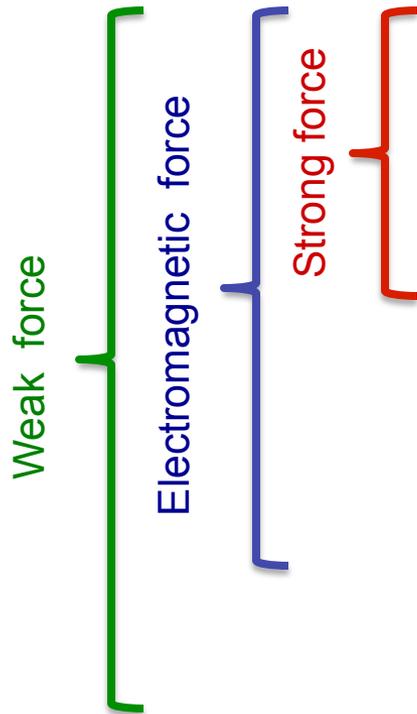
“ a particle is an irreducible representation of the inhomogeneous Lorentz group ”

(E. Wigner)

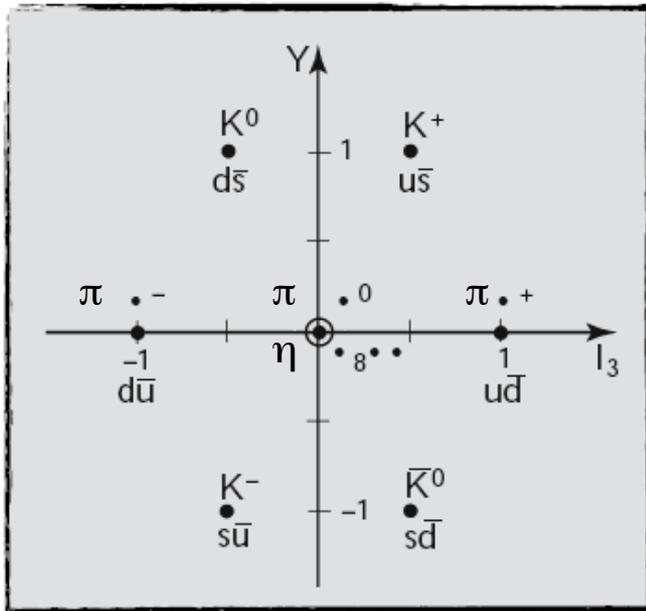
That means:

→ Spin 0, 1/2, 1, 3/2 & mass > 0

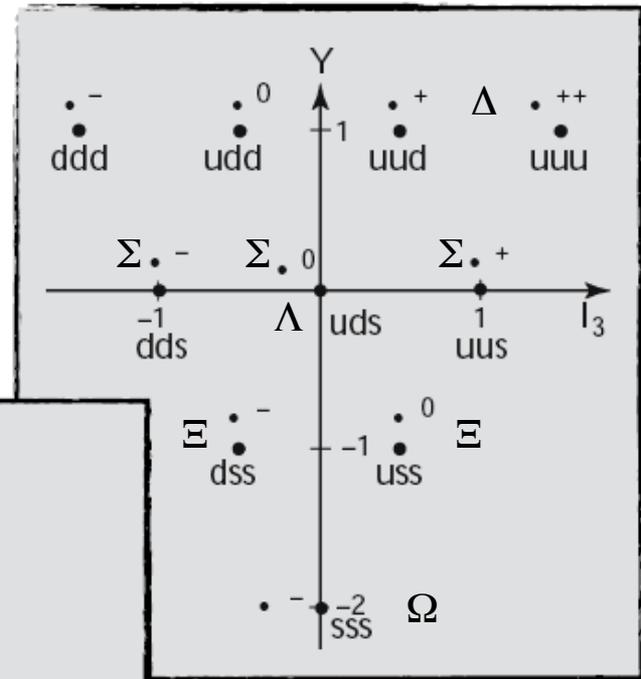
What is a Particle?



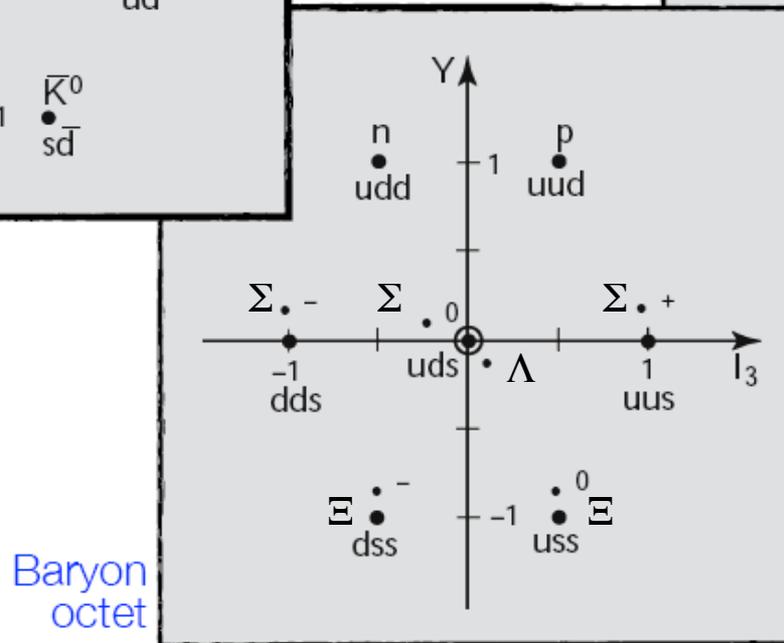
Barions & mesons



Meson octet

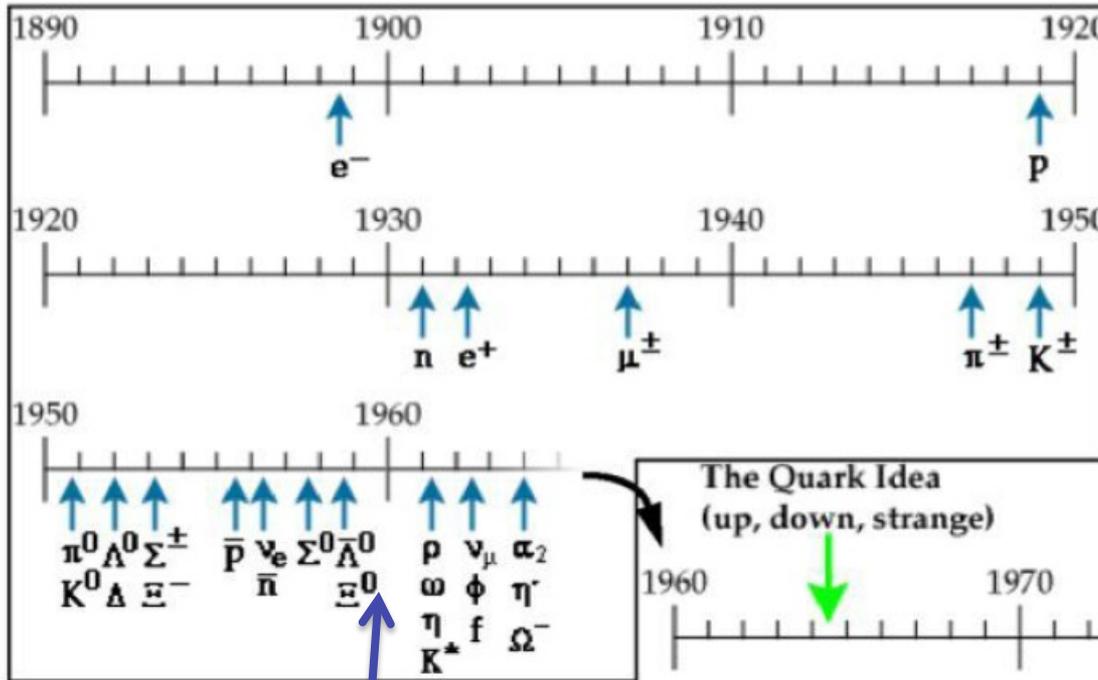


Baryon decuplet



Baryon octet

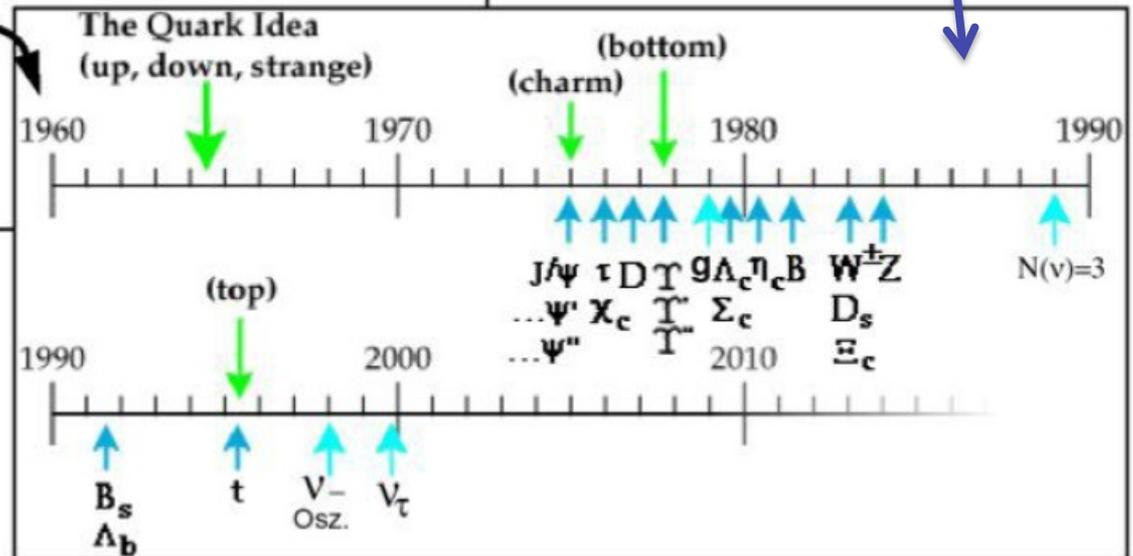
A history of discoveries



Today > 200 particles listed in PDG

But only 27 have $\tau > 1\mu\text{m}$
and only 13 have $\tau > 500\mu\text{m}$

Already 20 particles discovered



... image and logic discoveries

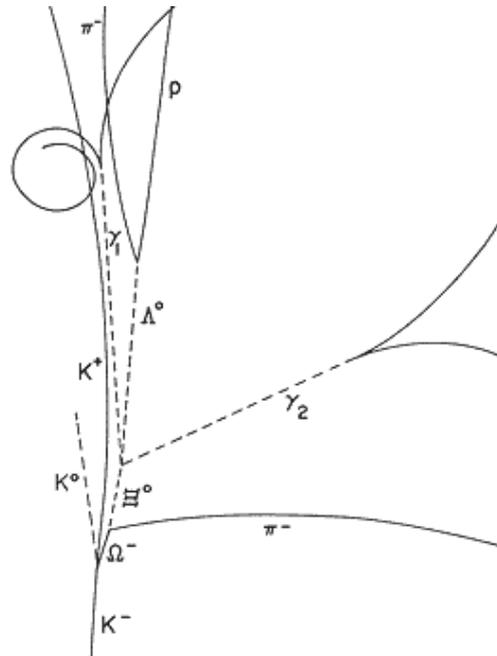
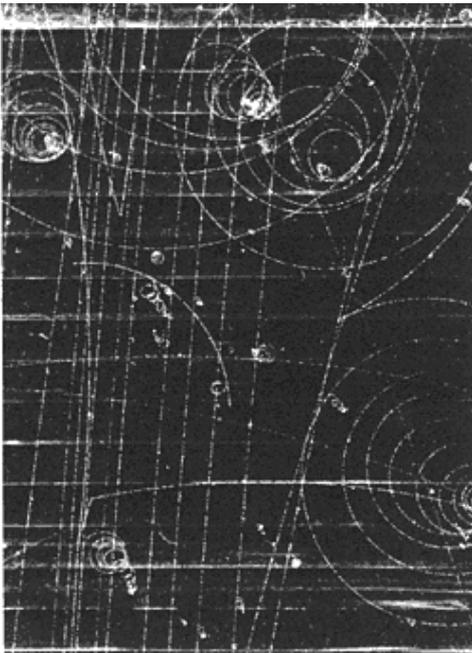
Particle detection

- The detector sees **only “stable” particles ($c\tau > 500\mu\text{m}$)**
- the 8 most frequently produced are:
 - $e^\pm, \mu^\pm, \gamma, \pi^\pm, K^\pm, K^0, p^\pm, n$
- In order to detect a particle, it has to interact - and deposit energy
- Ultimately, the signals are obtained from the interactions of charged particles
- Neutral particles (photons, neutrons) have to transfer their energy to charged particles to be measured
 - calorimeters

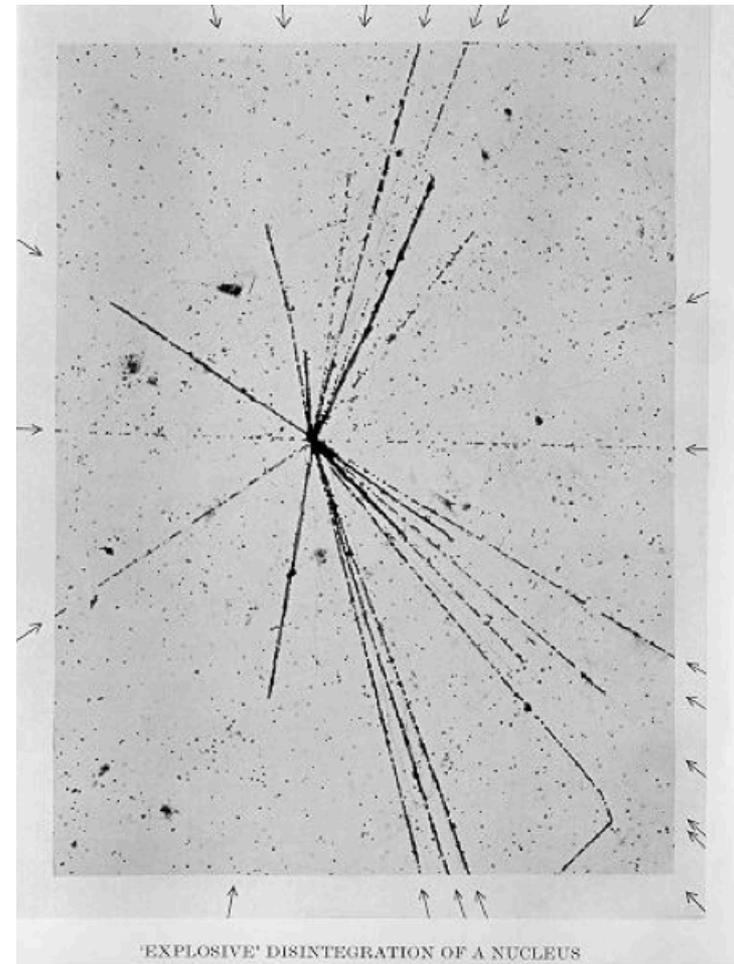
Image tradition

→ Led to the discovery of the first ~30 particles (long lived)

- Cloud chambers
- Emulsions
- Bubble chambers



Discovery of the Ω^- in 1964



'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

nuclear disintegrations in 1937

Particle discovery

By 1959: 20 particles

e^- : fluorescent screen

n : ionization chamber

7 Cloud Chamber:

e^+

μ^+, μ^-

K^0

Λ^0

Ξ^-

Σ^-

6 Nuclear Emulsion:

π^+, π^-

anti- Λ^0

Σ^+

K^+, K^-

2 Bubble Chamber:

Ξ^0

Σ^0

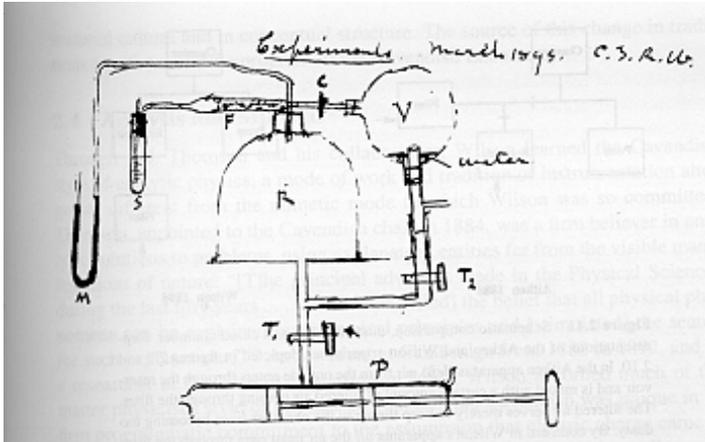
3 with Electronic techniques:

anti-n

anti-p

π^0

The tools of discovery



Cloud chamber, Wilson 1895

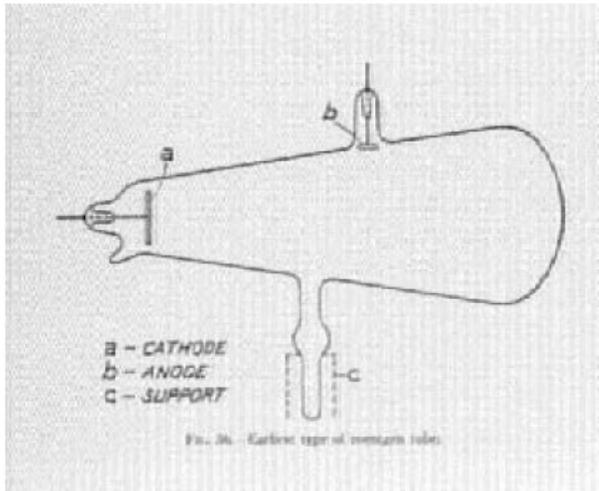
Charles Thomson Rees Wilson, * 1869, Scotland:

Wilson was a meteorologist who was, among other things, interested in **cloud formation initiated by electricity**.

In 1895 he arrived at the Cavendish Laboratory where **J.J. Thompson**, one of the chief proponents of the corpuscular nature of electricity, had studied the discharge of electricity through gases since 1886.

Wilson used a 'dust free' chamber filled with saturated water vapour to study the cloud formation caused by ions present in the chamber.

The tools of discovery



Conrad Röntgen discovered X-Rays in 1895.

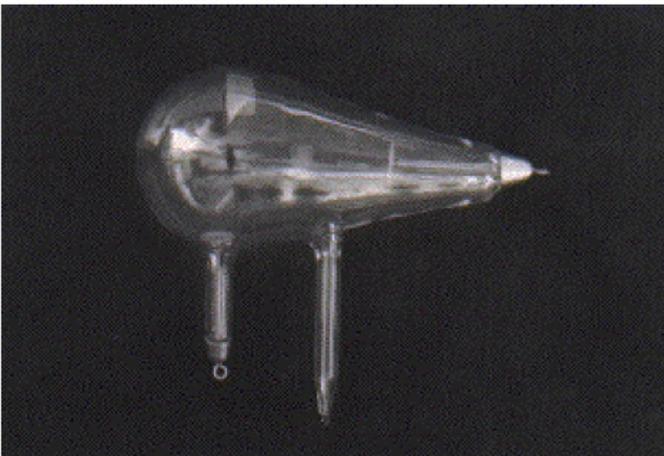
At the Cavendish Lab Thompson and Rutherford found that irradiating a gas with X-rays increased its conductivity suggesting that X-rays produced ions in the gas.

Wilson used an X-Ray tube to irradiate his Chamber and found 'a very great increase in the number of the drops', confirming the hypothesis that ions are cloud formation nuclei.

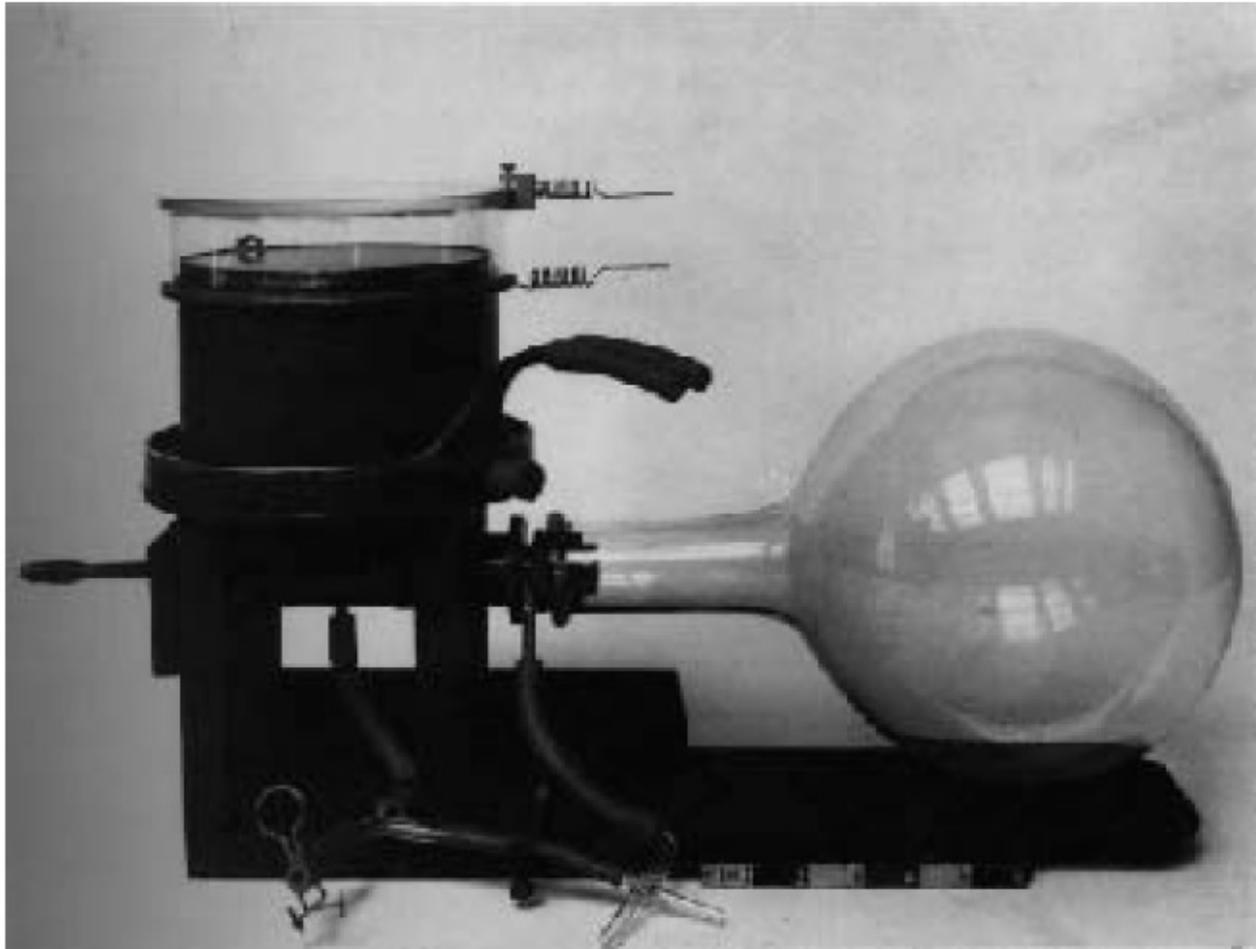
Radioactivity ('Uranium Rays') discovered by Becquerel in 1896. It produced the same effect in the cloud chamber.

1899 J.J. Thompson claimed that cathode rays are fundamental particles → electron [Nobel 1906].

Soon afterwards it was found that rays from radioactivity consist of alpha, beta and gamma rays (Rutherford).



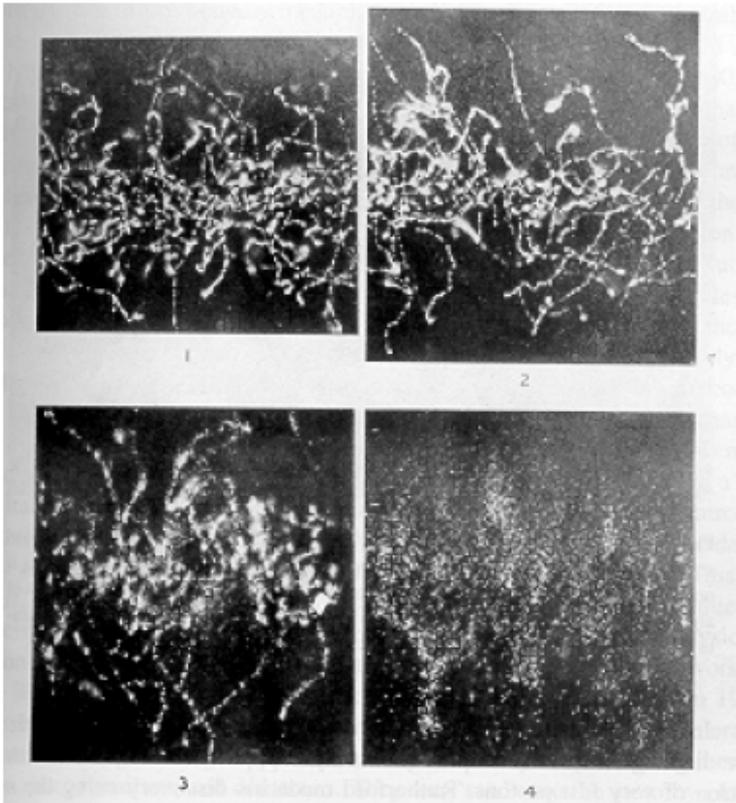
The cloud chamber



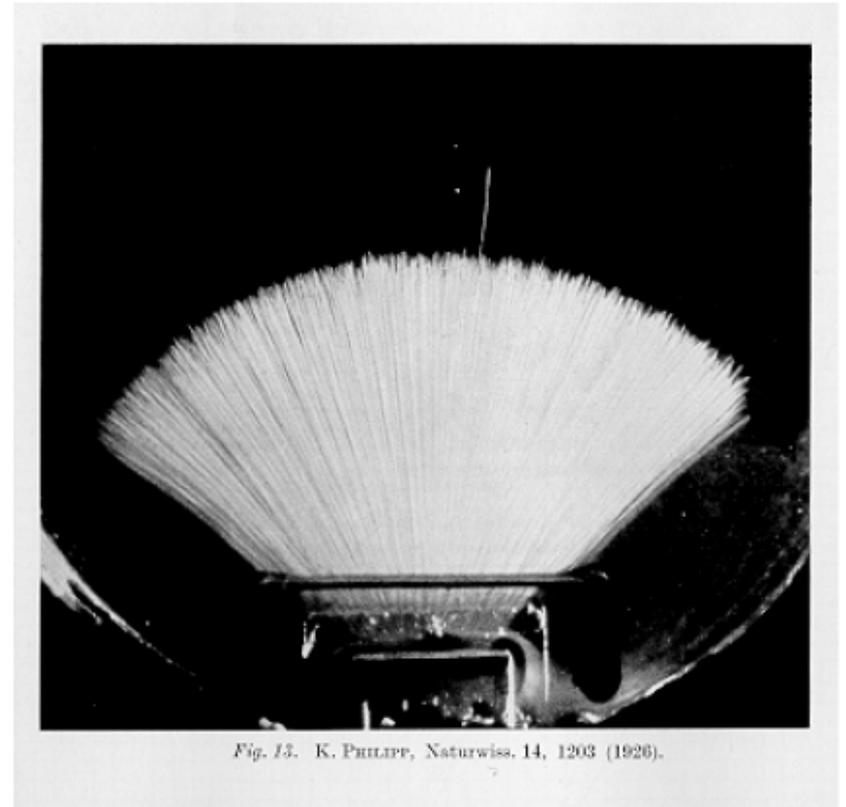
Wilson Cloud Chamber 1911

The cloud chamber

Combined with the invention of fast photography, one could record particle tracks in the cloud chamber → discoveries via imaging



X-rays, Wilson 1912



Alphas, Philipp 1926

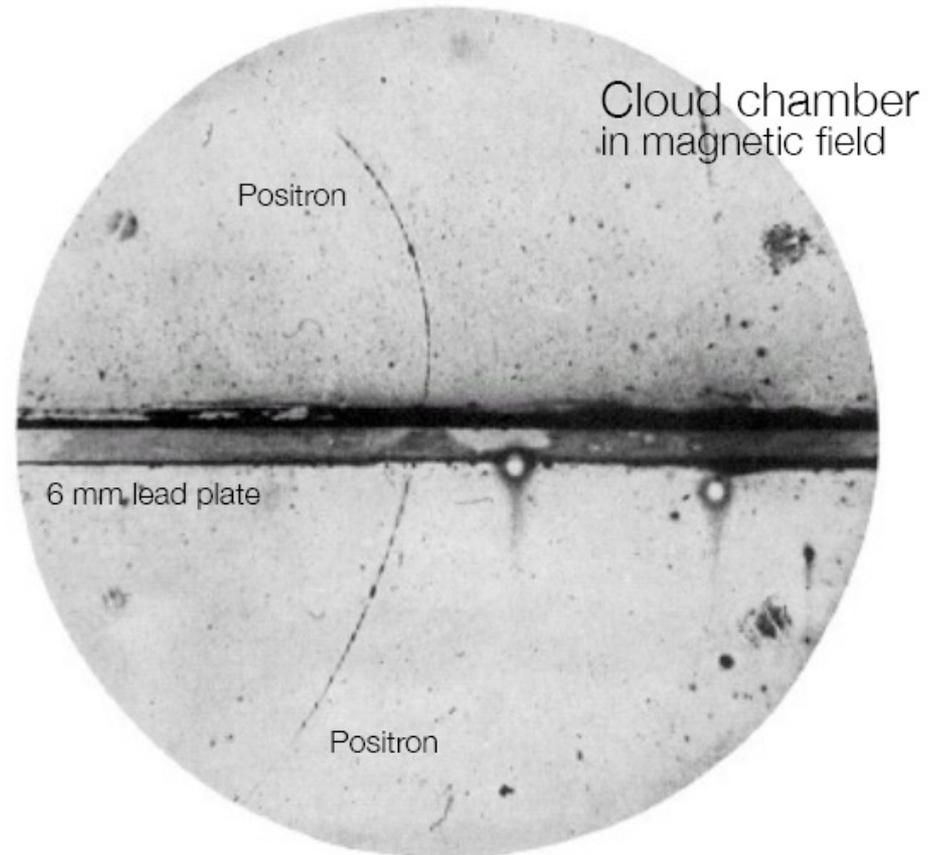
Important particle discoveries

**Positron discovery,
Carl Andersen 1933
[Nobel price 1936]**

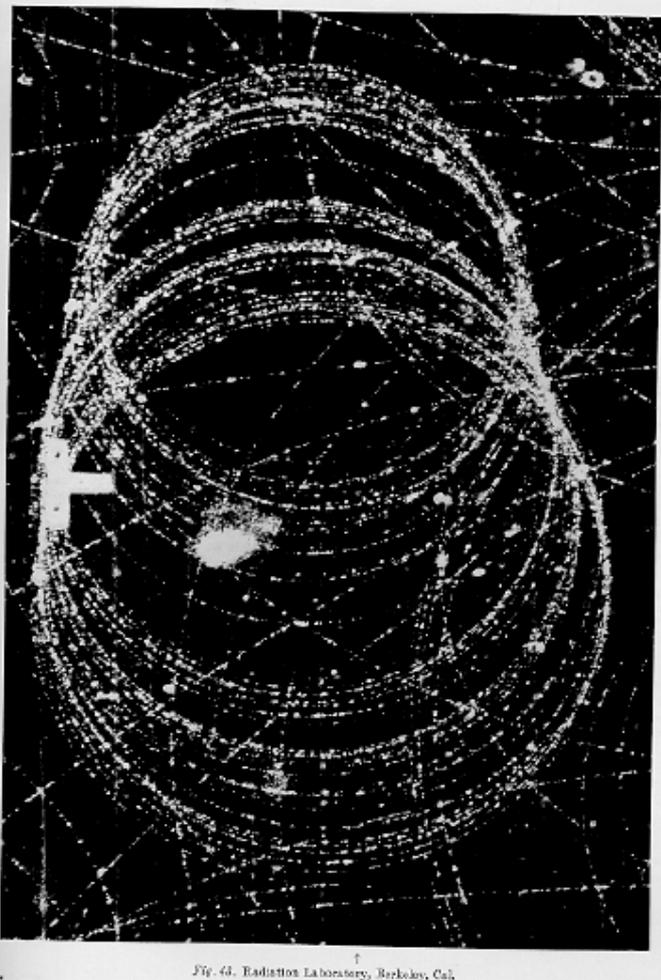
**Magnetic field 15000 Gauss,
chamber diameter 15cm.**

**A 63 MeV positron passes through a
6mm lead leaving the plate with
energy 23MeV.**

**The ionization of the particle, and its
behaviour in passing through the foil
the same as those of an electron.**



Important physics discovery



The picture shows an electron with 16.9 MeV initial energy. It spirals about 36 times in the magnetic field.

At the end of the visible track the energy has decreased to 12.4 MeV. From the visible path length (1030cm) the energy loss by ionization is calculated to be 2.8MeV.

The observed energy loss (4.5MeV) must therefore be caused in part by **Bremsstrahlung**.

The curvature indeed shows sudden changes as can most clearly be seen at about the seventeenth circle.

Important particle discoveries

Discovery of the pion

Nuclear emulsion technique

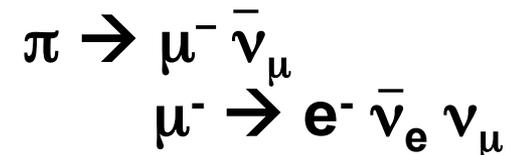
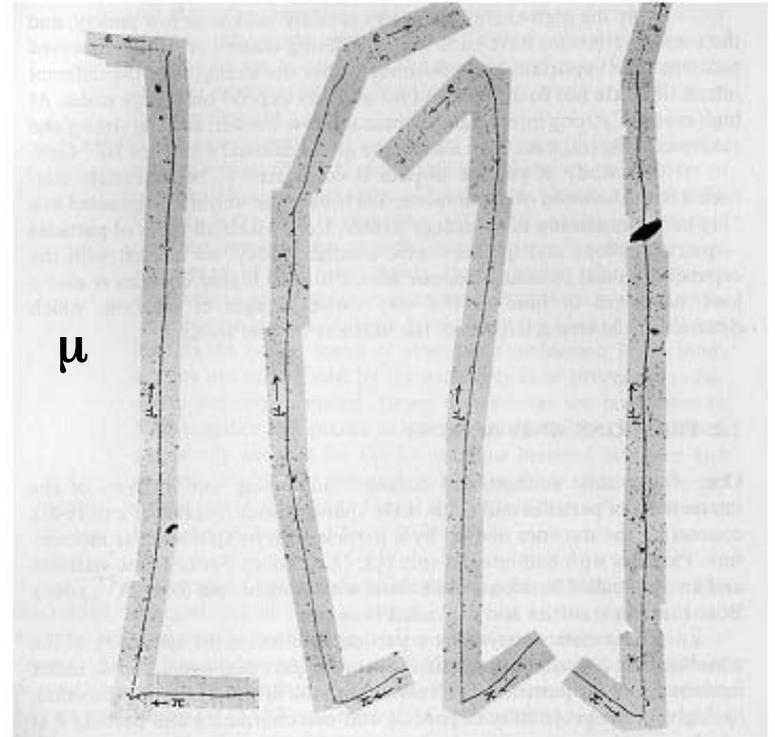
[Powell 1947; Nobel prize 1950]

The muon was discovered in the 1930ies and was first believed to be Yukawa's meson that mediates the strong force.

The long range of the muon was however causing contradictions with this hypothesis.

In 1947, Powell et. al. discovered the Pion in nuclear emulsions exposed to cosmic rays, and they showed that it decays to a muon and an unseen partner.

The constant range of the decay muon indicated a two body decay of the pion.



Intermezzo: why do we see muons on earth?

$$\mu^- \rightarrow e^- \nu_e \nu_\mu \quad \tau_\mu = 2.2 \cdot 10^{-6} \text{ s}, m_\mu c^2 = 105 \text{ MeV}$$

Produced by cosmic rays (p, He, Li ...) colliding with air in the upper atmosphere **~10 km**)

$$s = v \tau = 600 \text{ m} \rightarrow \text{no muon should reach Earth!}$$

But we see them ...

$$E_\mu = 2 \text{ GeV}, m_\mu c^2 = 105 \text{ MeV} \rightarrow \gamma \sim E/mc^2 \sim 19$$

$$s = v \gamma \tau = 12.5 \text{ km} \rightarrow \text{can reach Earth!}$$

$$\text{Pions:} \quad \tau_\pi = 2.6 \cdot 10^{-8} \text{ s}, m_\pi c^2 = 135 \text{ MeV}$$

$$s = v \gamma \tau = 115 \text{ m} \rightarrow \text{very rare on Earth}$$

→ Discovered in emulsion experiments on high mountains

Intermezzo: energy spectrum of 2-bodies decay



Initial

$$p = 0,$$

$$E = m_\pi c^2$$

Final

$$p_1 + p_2 = 0$$

$$E_1 + E_2 = E$$

2 unknown in 2 equations \rightarrow the energies are uniquely defined

2-bodies decay gives sharp energies for the two decay particles

Remember neutrino discovery in 1920ies in $n \rightarrow p e^- \nu_e$

Discovery of strange particles

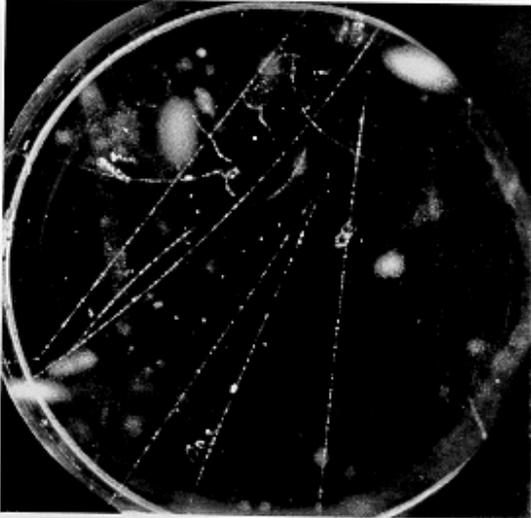


Plate 115

Particle momenta are measured by the bending in the magnetic field.

‘ ... The V0 particle originates in a nuclear Interaction outside the chamber and decays after traversing about one third of the chamber. The momenta of the secondary particles are $1.6 \pm 0.3 \text{ BeV}/c$ (now GeV/c) and the angle between them is 12 degrees ... ‘

By looking at the specific ionization one can try to identify the particles and by assuming a two body decay one can find the mass of the V0.

‘ ... if the negative particle is a negative proton, the mass of the V0 particle is $2200 m_e$, if it is a π or μ Meson the V0 particle mass becomes about $1000 m_e$... ‘

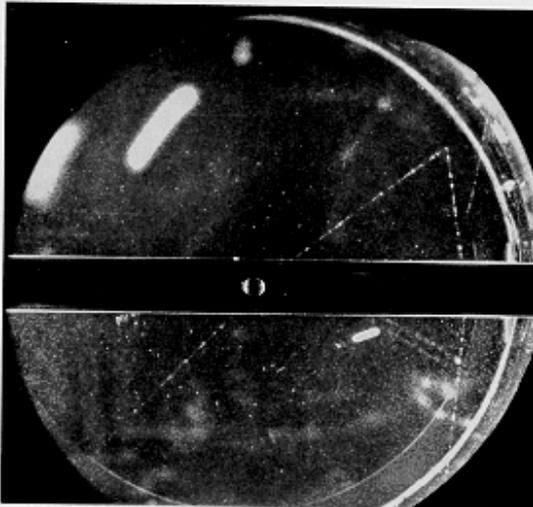


Plate 116

Rochester and Wilson

From image to electronic detectors

- With the latest bubble chambers position resolution $\sim 5\mu\text{m}$
- Best reconstruction of complex decays
- But low rate capability \sim few tens / second (LHC $\sim 10^9$ collisions/s)
- Imaging detectors cannot be triggered selectively
 - every image must be photographed (and analyzed)
- In the 70ies the logic (**electronic**) **detectors** took over
 - Geiger counters
 - Scintillator + photomultipliers
 - Spark counters

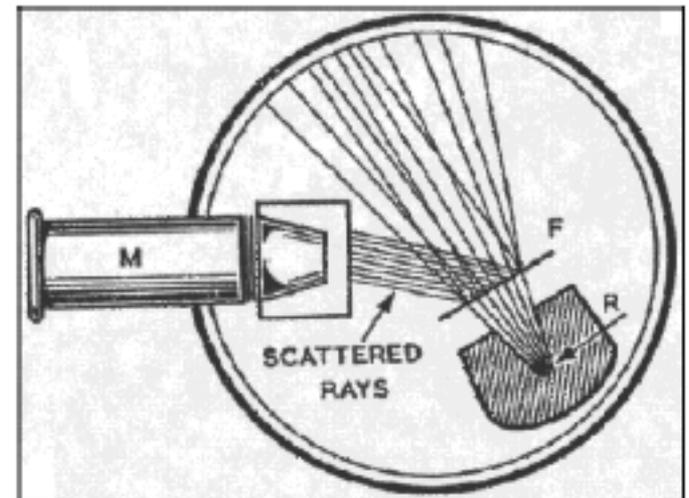
Logic (electronic) tradition

- The particle is not “seen” but its nature and existence “deduced” via a logic experiment (coincidences, triggers, detection of decay products ...)

Scintillating Screen:

Rutherford Experiment 1911, Zinc Sulfide screen was used as detector.

If an alpha particle hits the screen, a flash can be seen through the microscope.

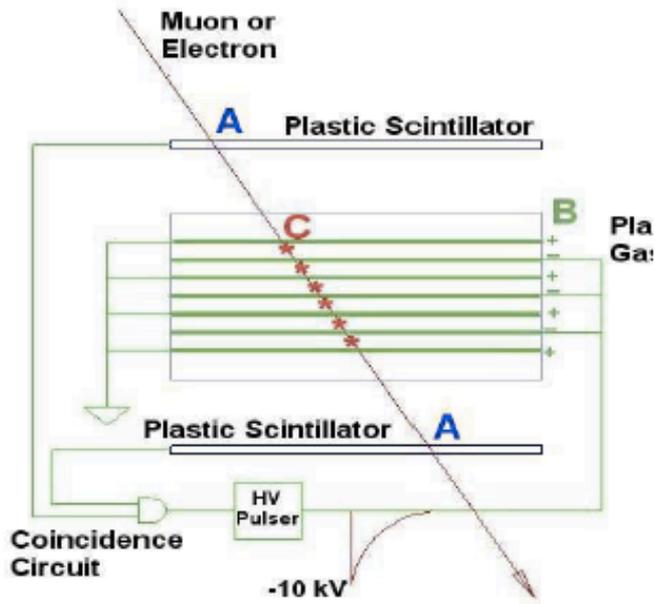


Important particle discoveries

The Spark Chamber was developed in the early 60ies.

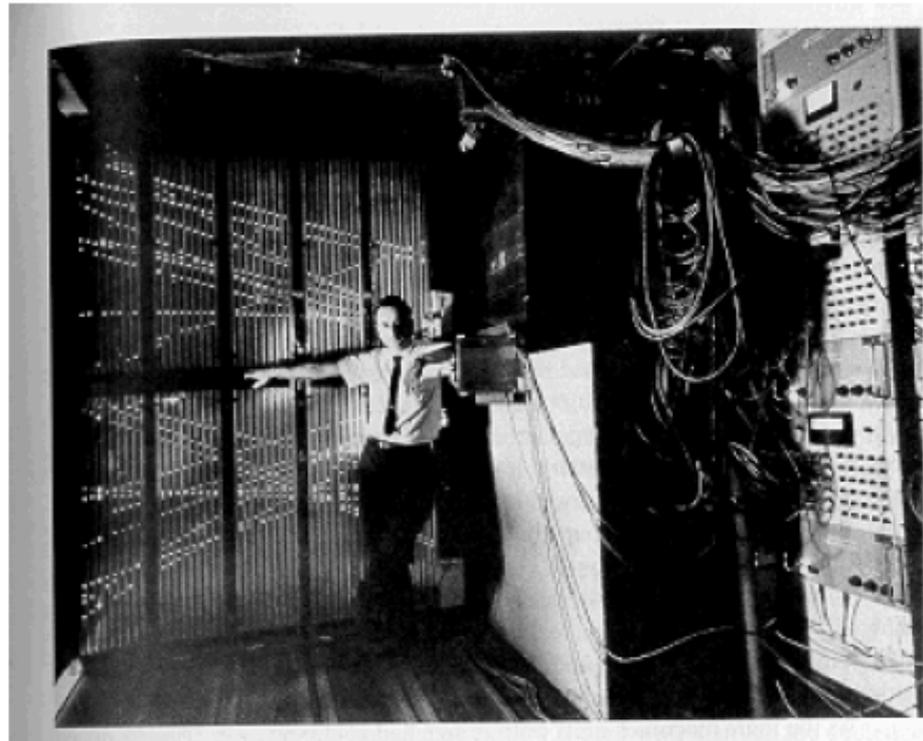
Schwartz, Steinberger and Lederman used it in discovery of the muon neutrino

Pions from AGS (Brookhaven) decay in flight into muon and neutrino. 5,000-ton steel wall stops muons. Neutrinos detected as spark trails due to the impact on aluminum plates in a neon-filled detector.

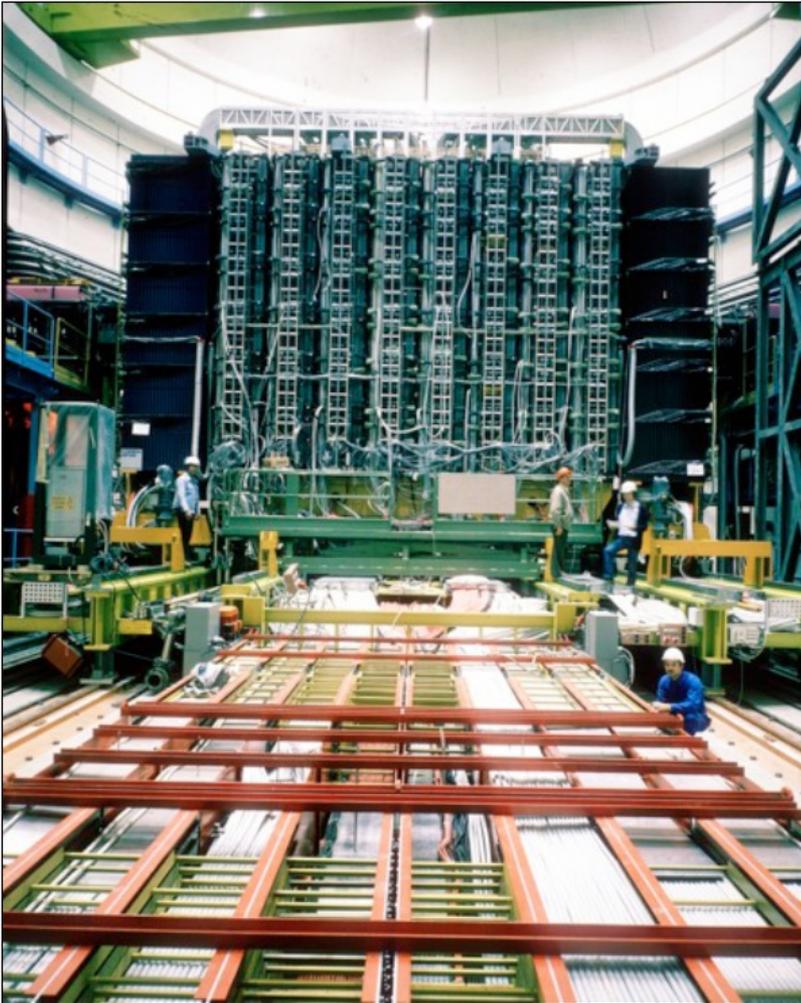


A charged particle traverses the detector and leaves an ionization trail.

The scintillators trigger an HV pulse between the metal plates and sparks form in the place where the ionization took place.



The merge of Electronic Images



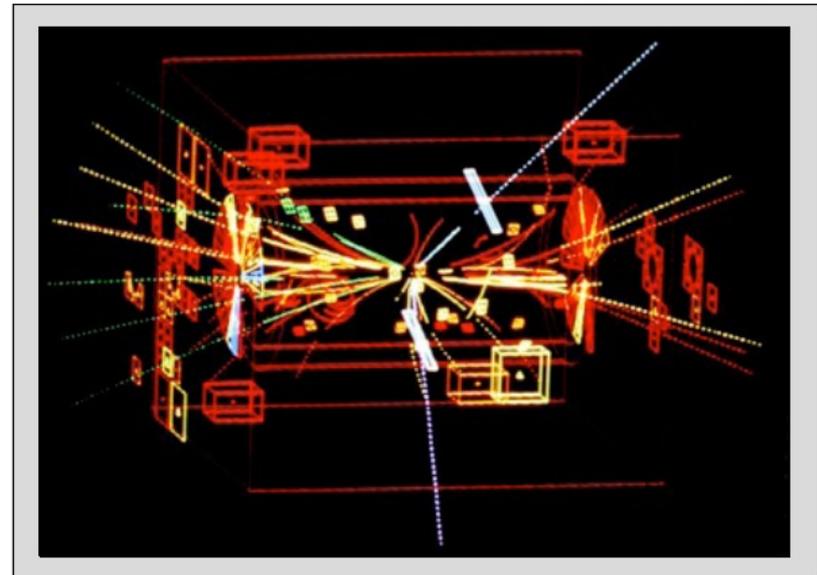
UA1
Detector

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

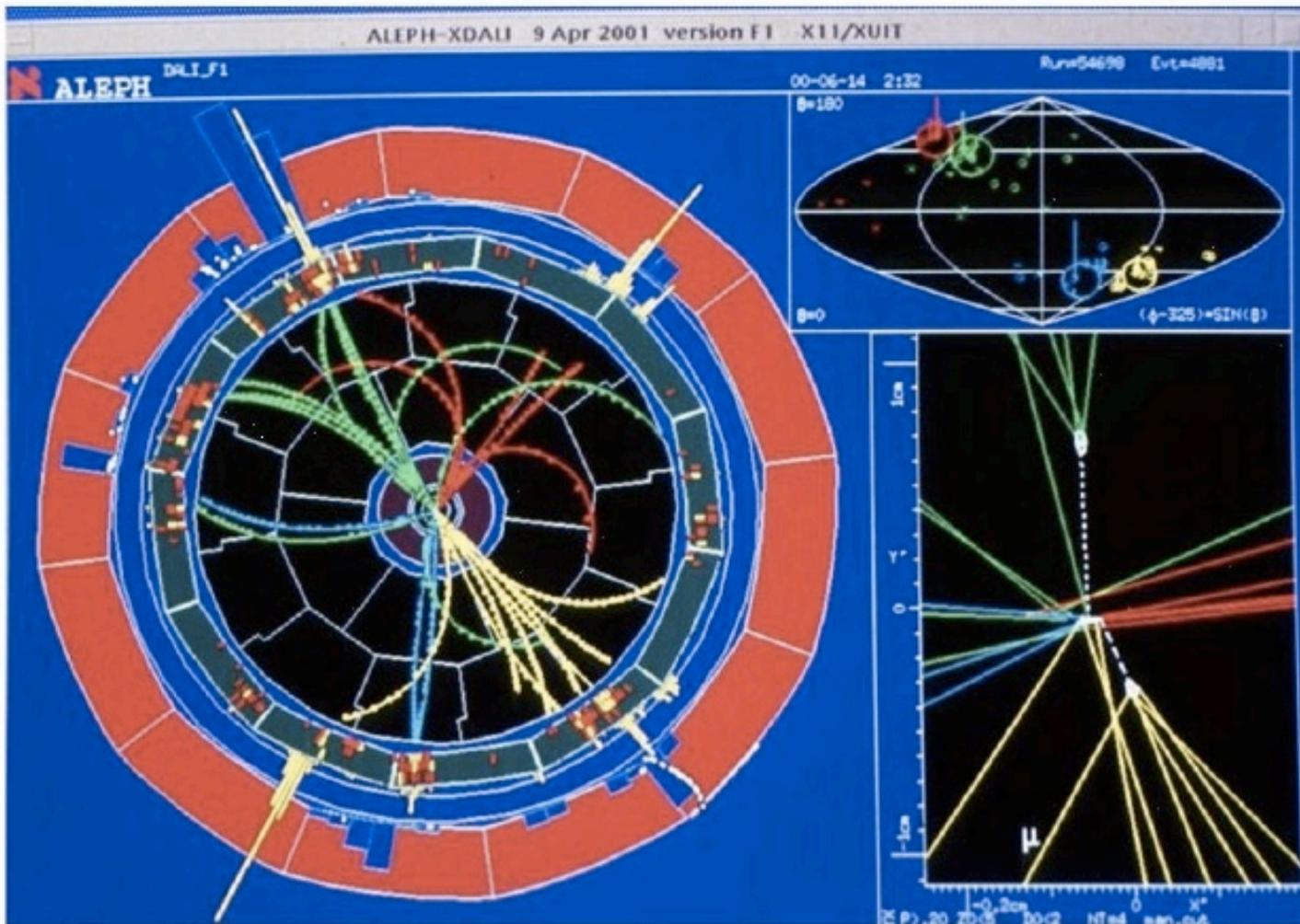
First Z^0 particle seen by UA1



$$Z_0 \rightarrow e^+e^-$$

LEP 1988 - 2000

Aleph Higgs Candidate Event: $e^+ e^- \rightarrow HZ \rightarrow bb + jj$

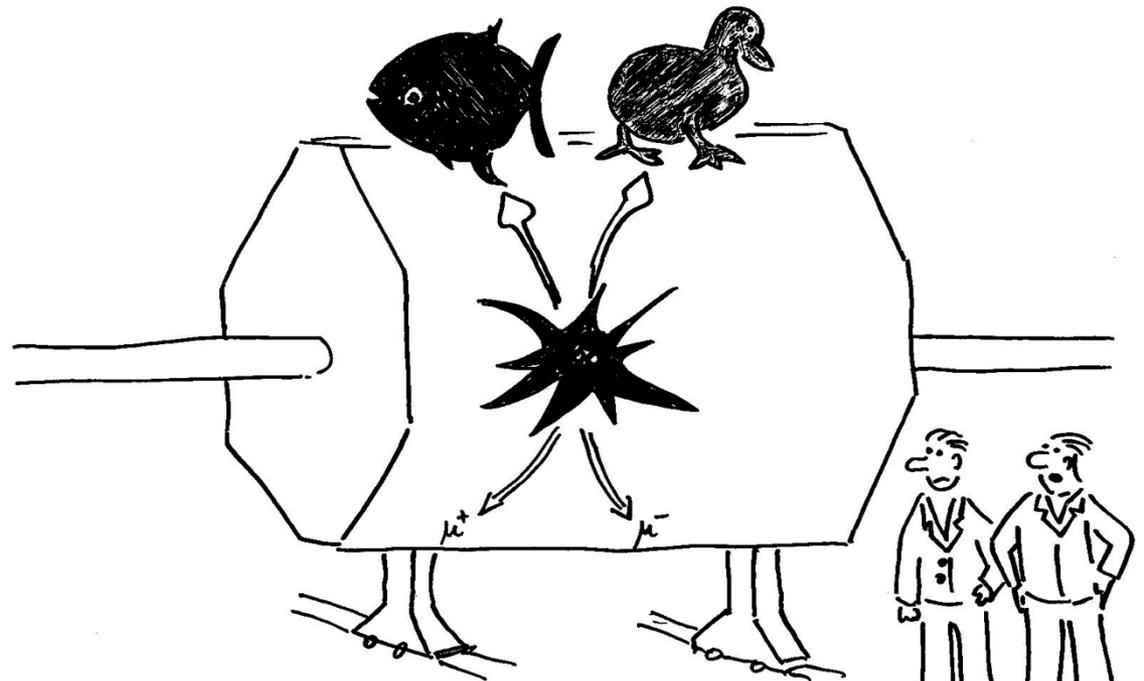


Important particle discoveries ... continues

Discovery of the Higgs boson (20XX)

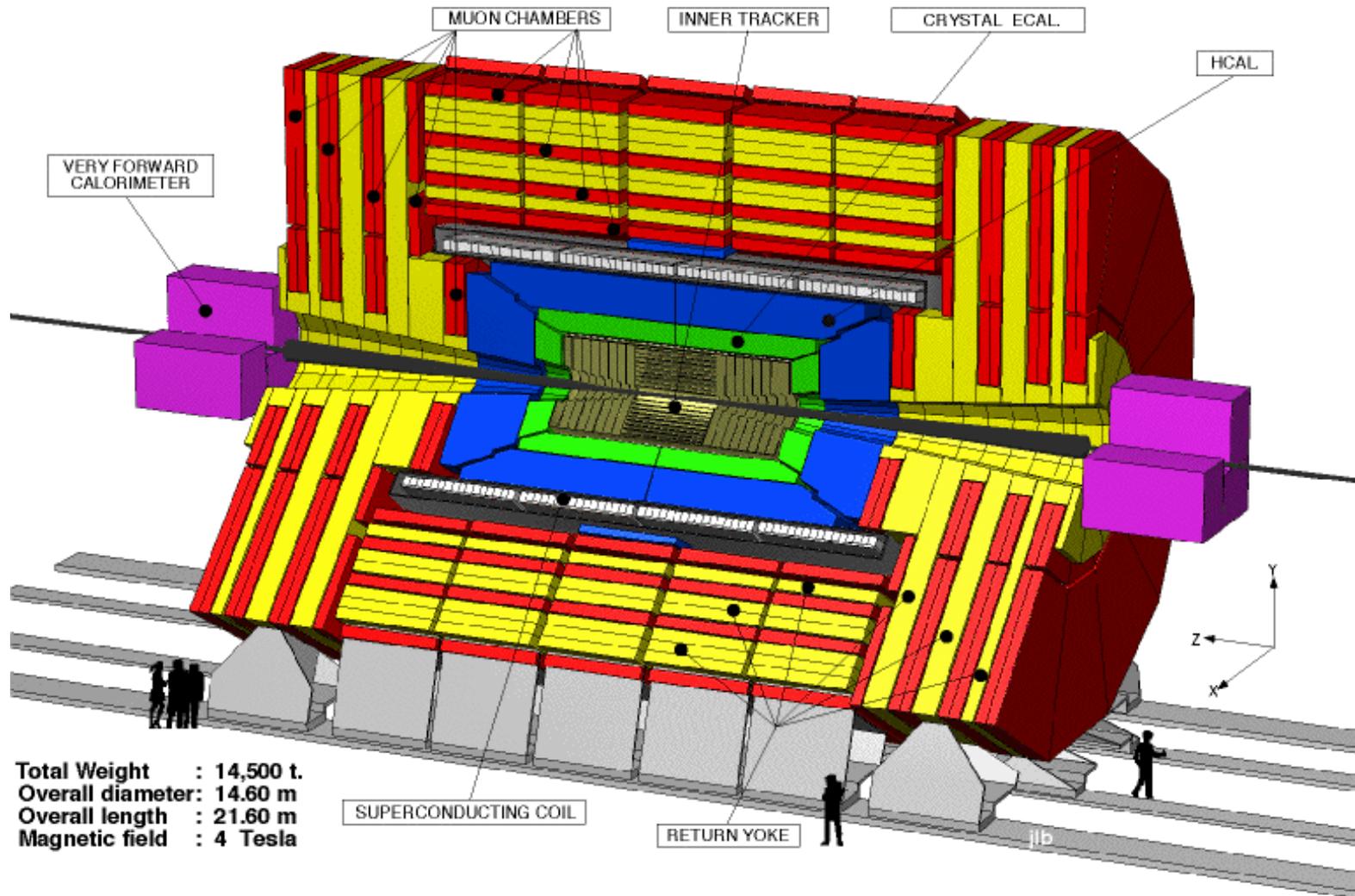
ATLAS and CMS collaborations

[P. Higgs, Nobel 20YY]



“This is not exactly, what theory predicted for the Higgs decay!”

Multi-purpose detectors (LHC 2009 - ...)



Preliminary definition

The Physics of Particle Detectors

What is a Particle?

What is a Detector?

A particle detector is an instrument to measure one or more properties of a particle ...

Properties of a particle:

- position and direction
- momentum
- energy
- mass
- velocity
- transition radiation
- spin, lifetime

x, \vec{x}
 $|\vec{p}|$
 E
 m
 β
 γ

Type of detection principle:

position and tracking
tracking in a magnetic field
calorimetry
Spectroscopy and PID
Cherenkov radiation or time of flight
TRD

Fundamental questions

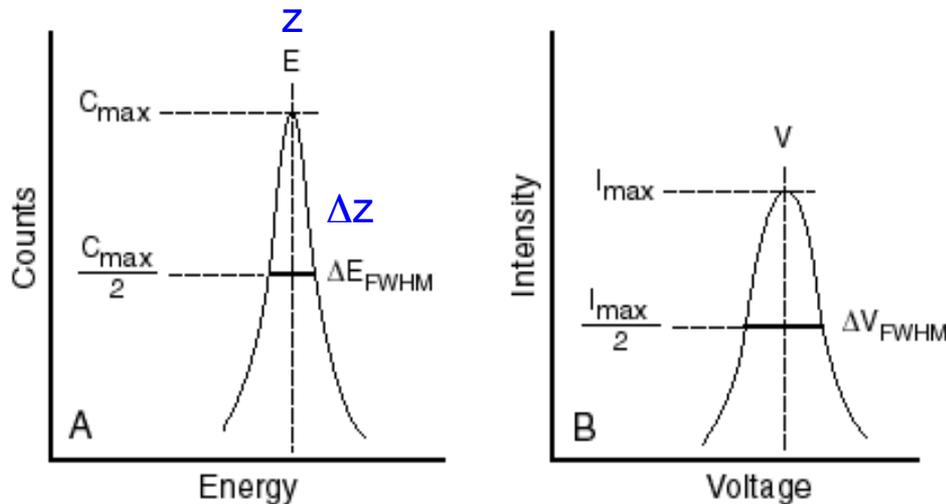
- Which kind of “particle” we have to detect?
- What is the required dimension of the detector?
- Which “property” of the particle we have to know?
 - Position
 - Time
 - Number
 - Energy
 - Polarity

with which resolution?
- What is the maximum count rate?
- What is the “time distribution” of the events?

Quality of measurements: resolution

Resolution generally defined as 1 standard deviation (1σ) for a Gaussian distribution, or the FWHM (Δz) $\sigma_z = \Delta z / 2.355$

If the measurement is dominated by Poissonian fluctuations:



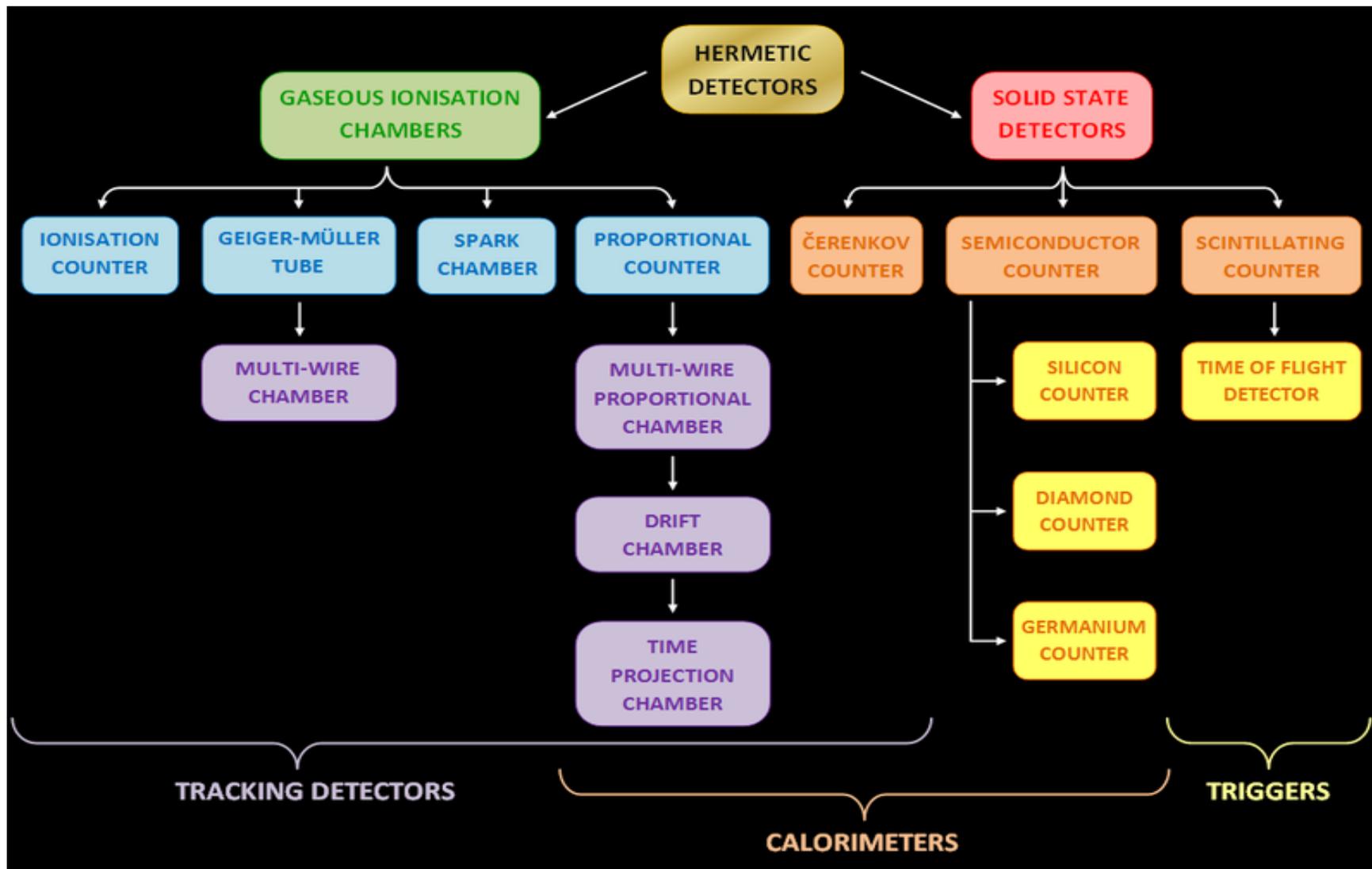
$$\frac{\sigma_z}{\langle z \rangle} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

→ Lowest limit for the resolution apart from Fano factor correction (...later)

What if the distribution is not Gaussian ?

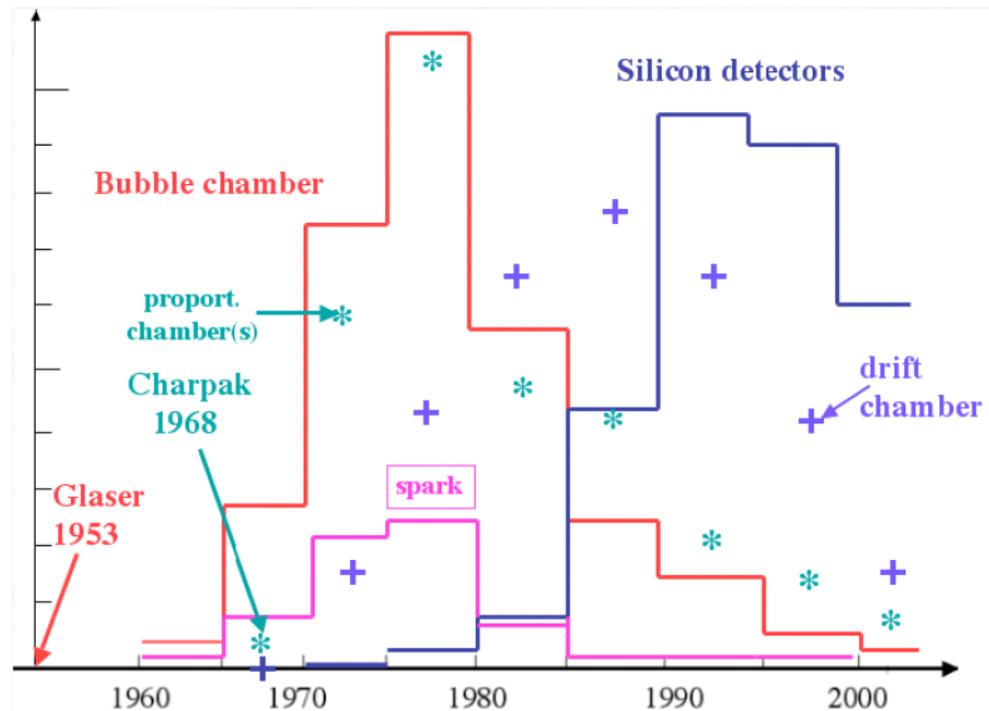
- Box distribution: $\sigma_z = \Delta z / \sqrt{12}$
- Other distributions: RMS, RMS_{90} , Quartiles

The detector zoo

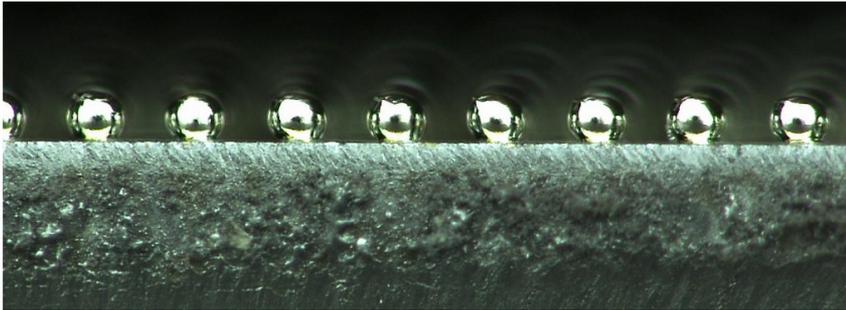


History of detectors (ex. trackers)

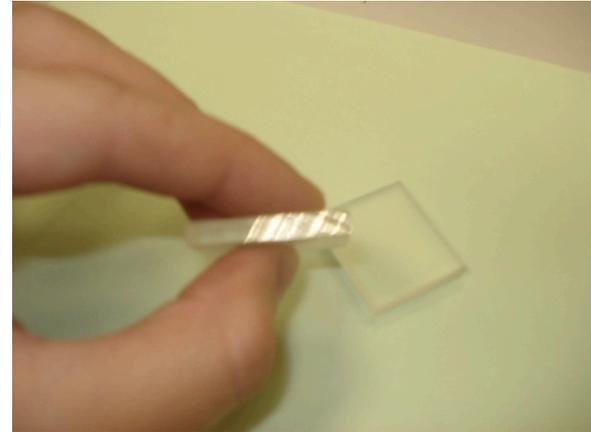
- **Cloud Chambers** dominating until the 1950s
→ now very popular in public exhibitions related to particle physics
- **Bubble Chambers** had their peak time between 1960 and 1985
→ last big bubble chamber was BEBC at CERN (Big European Bubble Chamber), now in front on the CERN Microcosm exhibition
- **Wire Chambers** (MWPCs and drift chambers) started to dominate since 1980s
- Since early 1990s solid state detectors are in use started as small sized vertex detectors
→ now ~200 m² silicon surface in CMS tracker



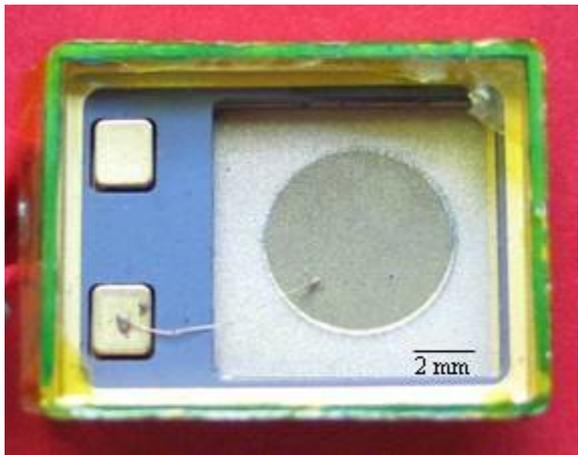
Future of detectors (the jewelry gallery)



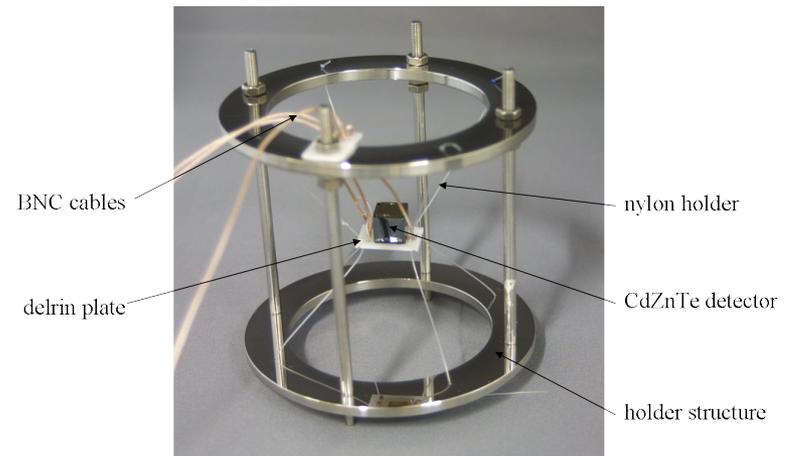
Gold bump bonding



Sapphire as calorimeter



Diamond as beam monitor and future Pixel detector

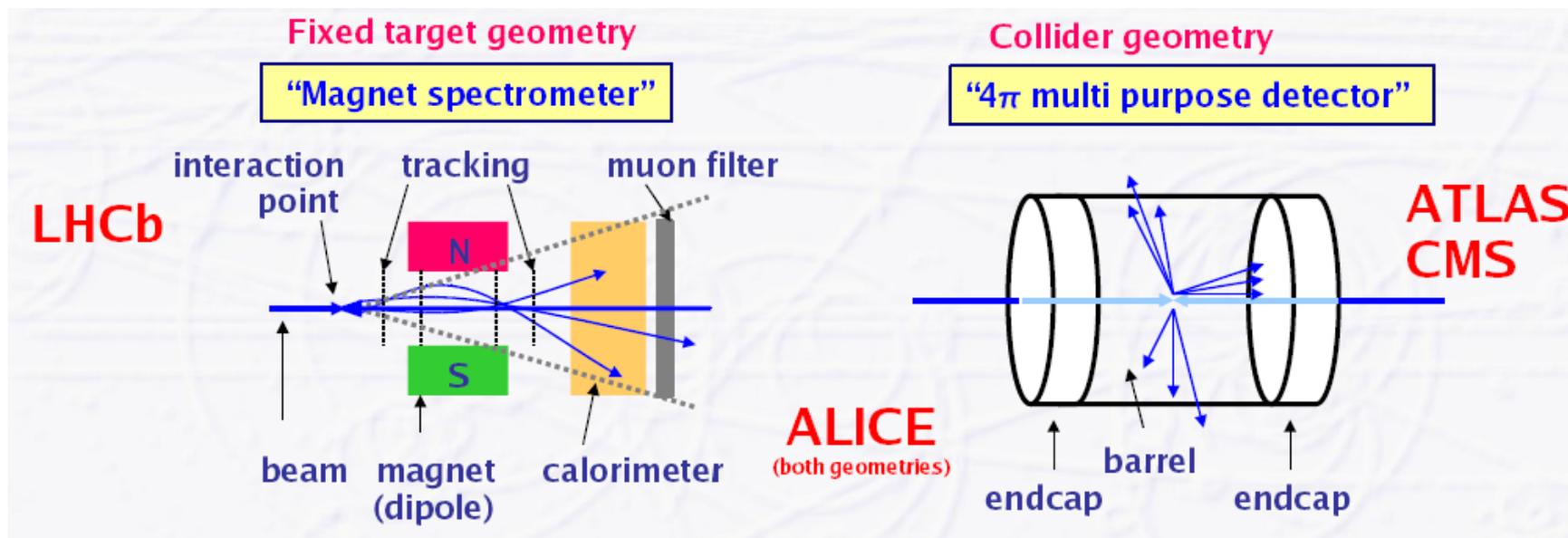


Cadmium zinc telluride bolometers for neutrino-less double beta decay

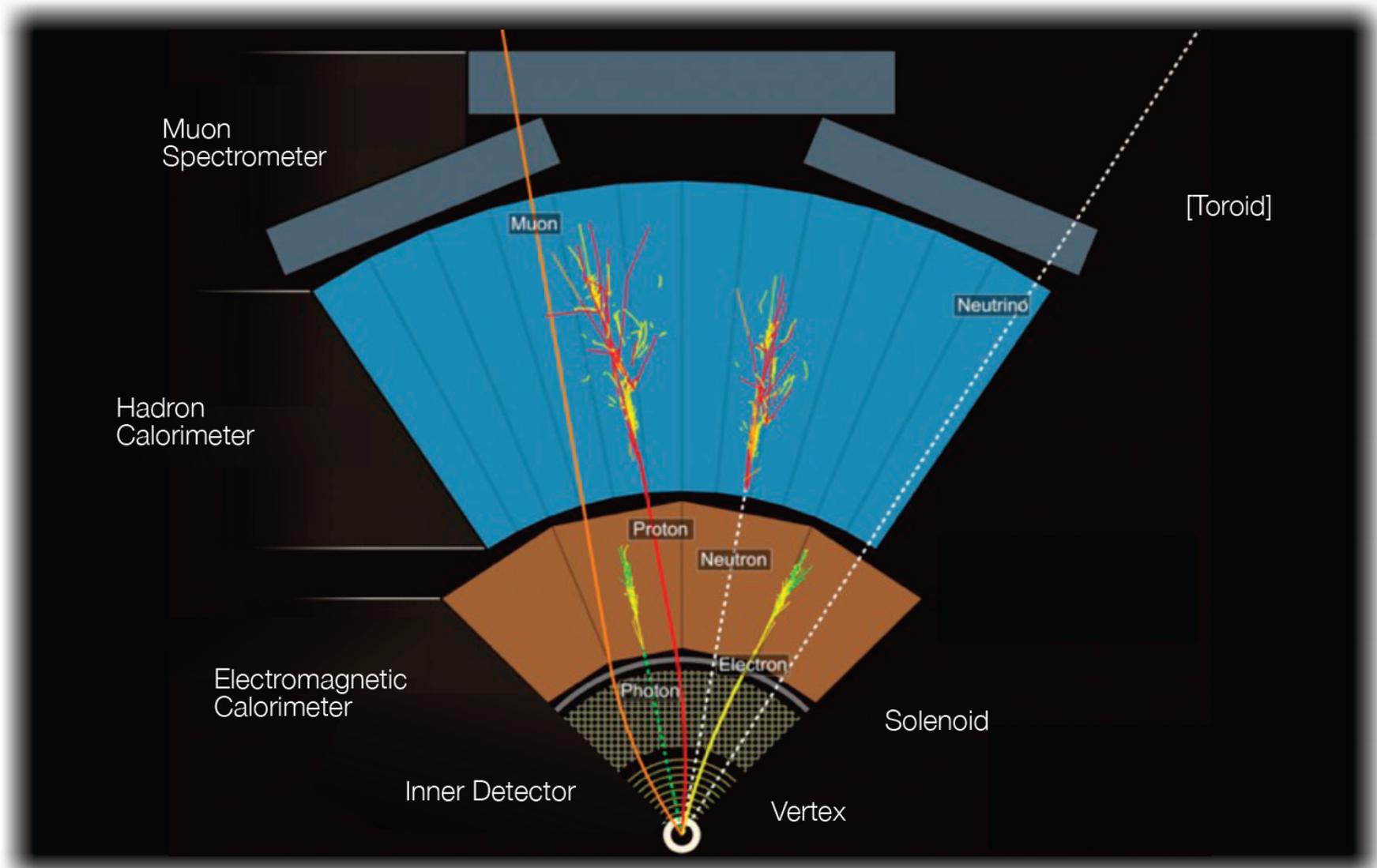
HEP detectors

A perfect detector should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get “4-momenta” of basic physics interaction)

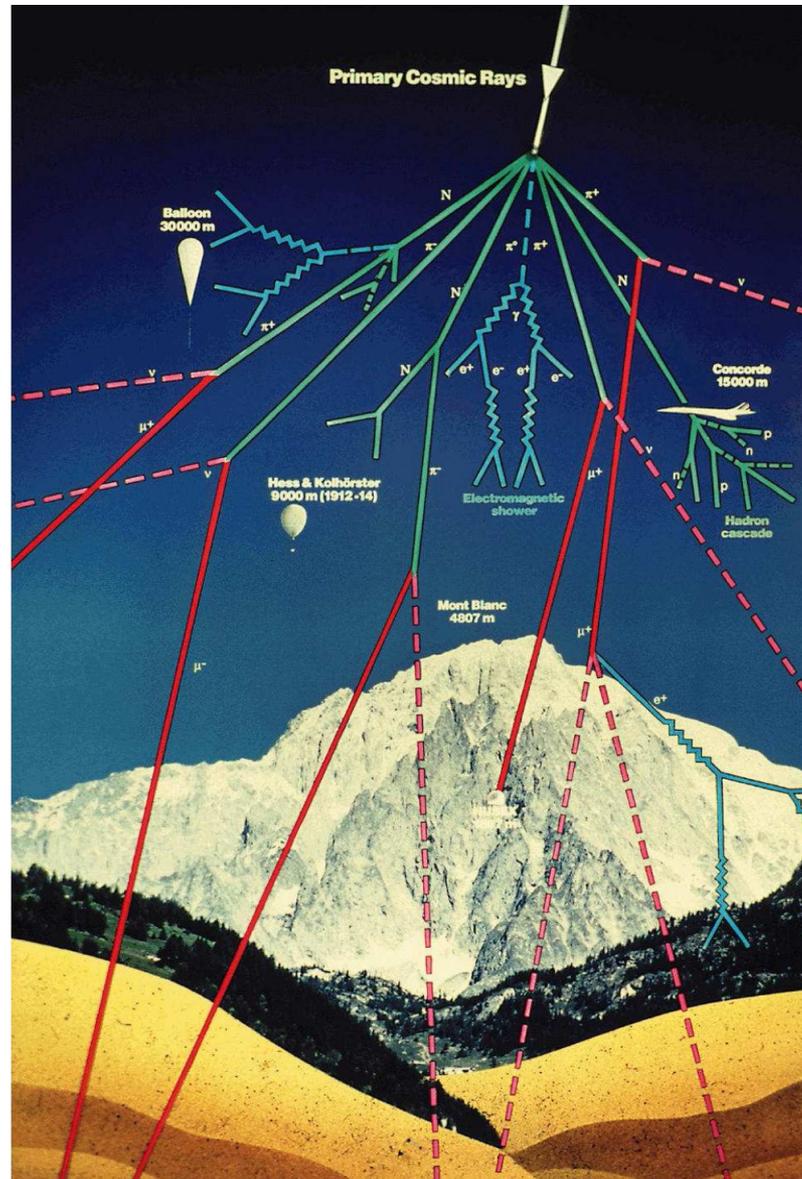
Efficiency: not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, electronics, mechanics)



Particle detector: detector system @ colliders

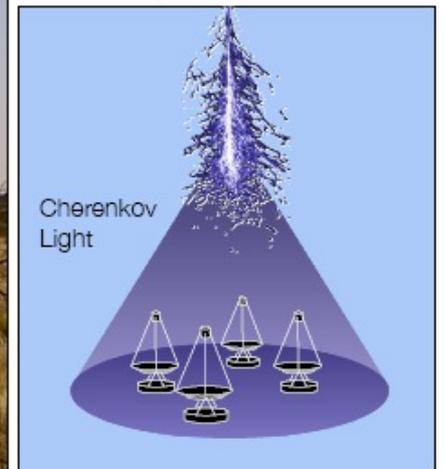
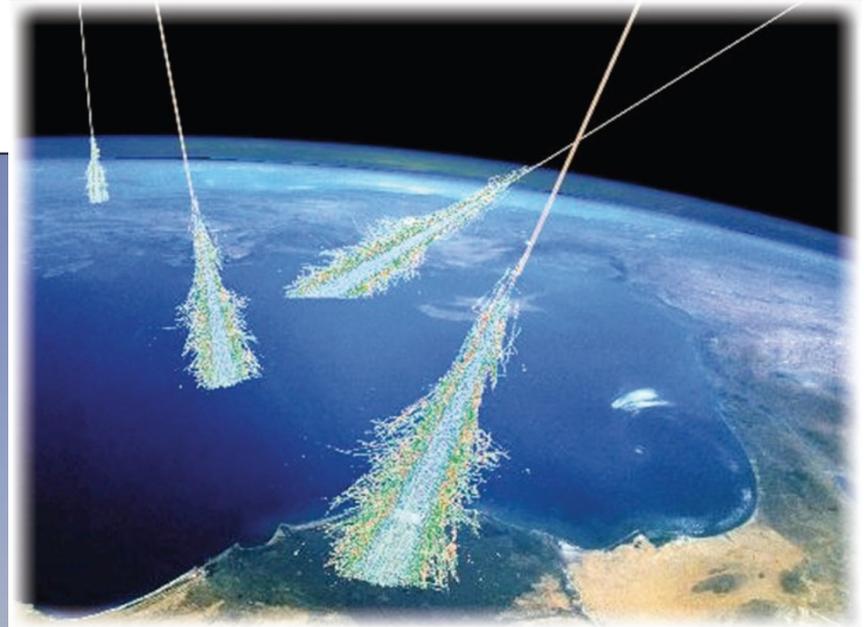


Astro-particle physics

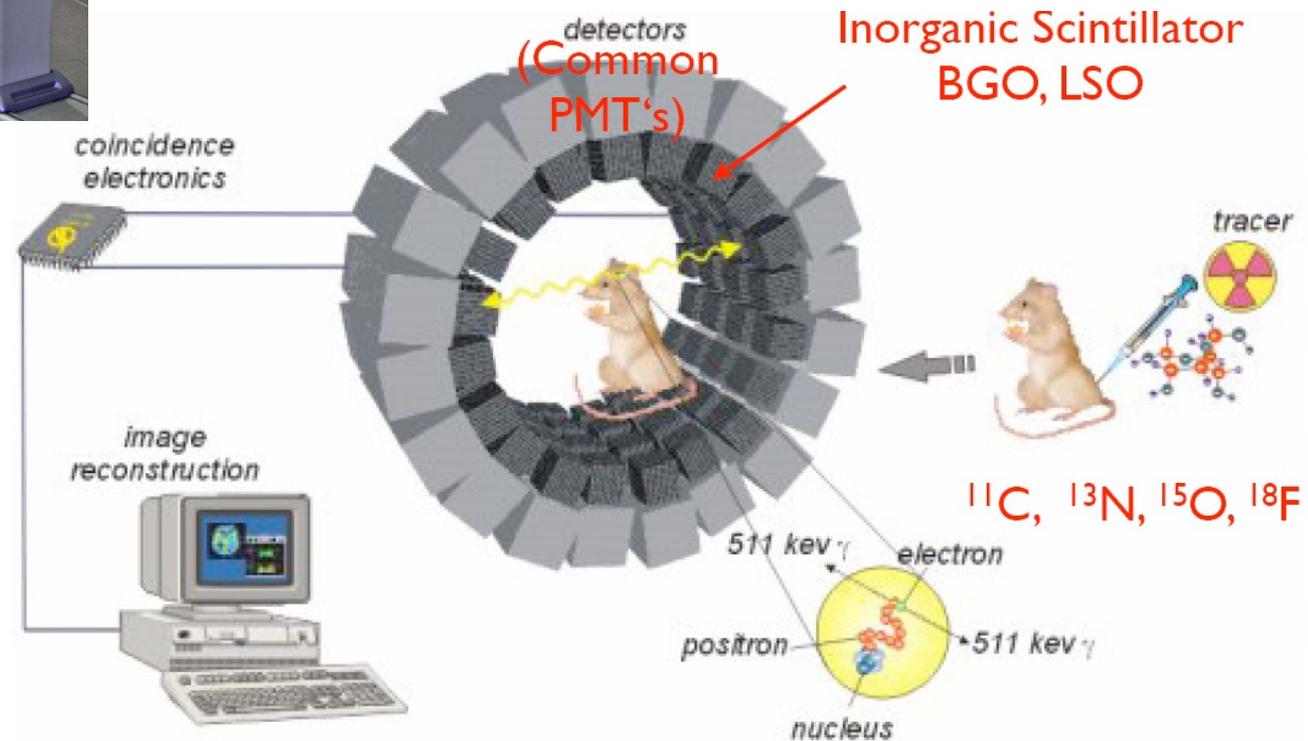
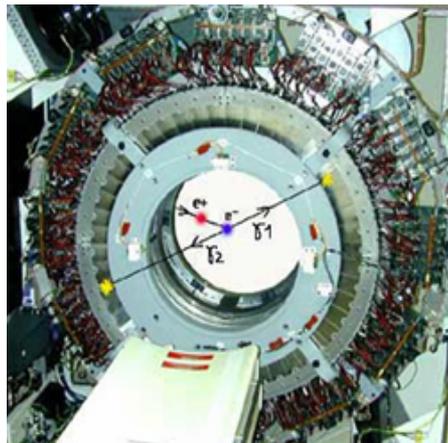


Particle detector: Cosmic rays detector

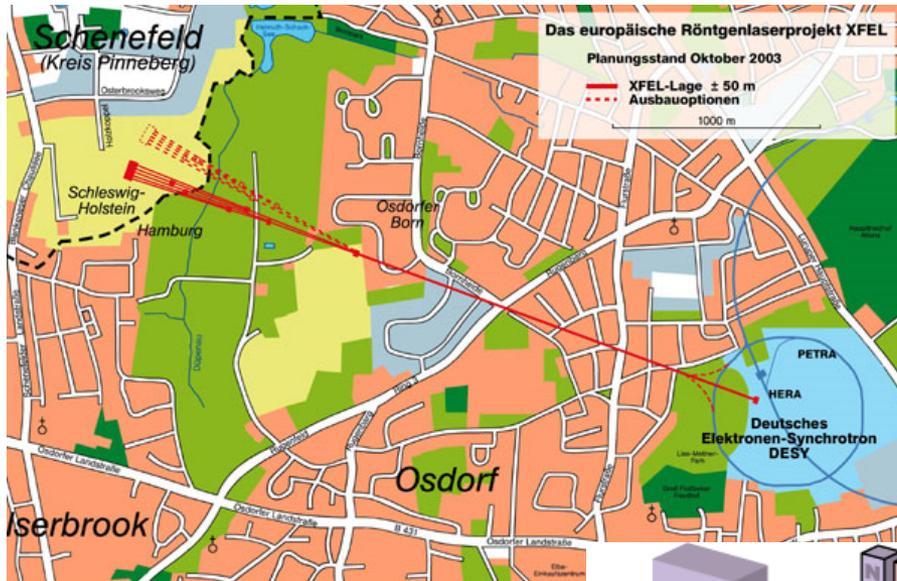
HESS telescope, Namibia



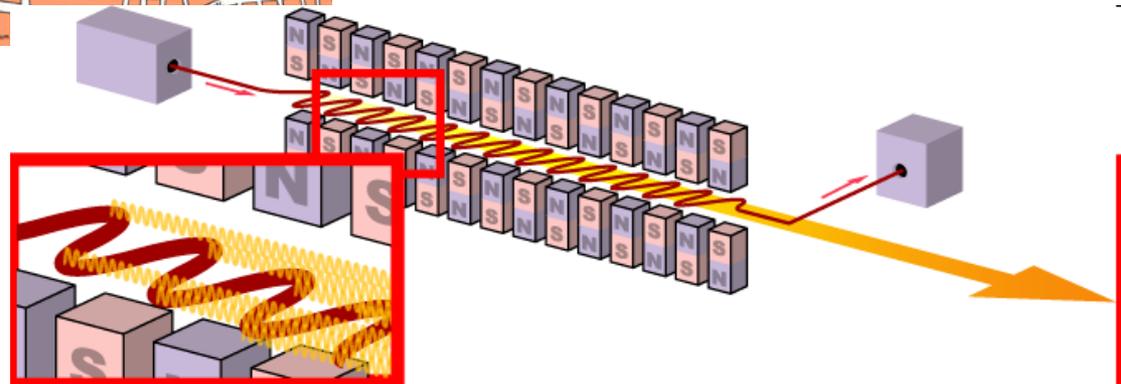
Particle detector: positron emission tomography



Particle detector: photon science



photon energy: 3-12 keV
wavelength: 0.1-0.3 nm
pulse duration (FWHM): 100 fs
average flux of photons: $3.6 \times 10^{16}/s$
number photon per pulse: 1.2×10^{12}
peak power: 24 GW



Summary

- 100 years of particle physics & discoveries possible thanks to a large variety of instruments and techniques
- Imaging devices are unbeatable in precision but slow & cannot be triggered
- Logic devices still largely in use (Geiger counters, scintillators, Cherenkov detectors)
- Today's particle detectors merge all possible techniques to create “electronic images” of particles
- In order to detect a particle, it has to interact - and deposit energy
 - ➔ all means are good = use all types of interaction

Acknowledgments

Large part of the content of this lecture is taken from Peter Galison, *Image and Logic a material culture of microphysics* and Werner Riegler (CERN)

BACKUP

Measuring particles

Particles are characterized by

Mass	[Unit: eV/c ² or eV]
Momentum	[Unit: eV/c or eV]
Energy	[Unit: eV]
Charge	[Unit: e]
[+ Spin, Lifetime ...]	

$$\begin{aligned} \text{eV} &= 1.6 \cdot 10^{-19} \text{ J} \\ c &= 299\,792\,458 \text{ m/s} \\ e &= 1.602176487(40) \cdot 10^{-19} \text{ C} \end{aligned}$$

Relativistic kinematics:

$$E^2 = \vec{p}^2 c^2 + m^2 c^4$$

$$\beta = \frac{v}{c} \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

$$E = m\gamma c^2 = mc^2 + E_{\text{kin}}$$

$$\vec{p} = m\gamma\vec{\beta}c \quad \vec{\beta} = \frac{\vec{p}c}{E}$$

Particle Identification via
measurement of

e.g. (E, \vec{p}, Q) or (\vec{p}, β, Q)
 (\vec{p}, m, Q) ...

Measuring particles [Units]

Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c ²	$1.78 \cdot 10^{-27}$ kg
$\hbar=h/2$	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ Js
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^8$ m/s
$\hbar c$	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ Jm

Natural units ($\hbar = c = 1$)		
mass	1 GeV	
length	$1 \text{ GeV}^{-1} = 0.1973 \text{ fm}$	
time	$1 \text{ GeV}^{-1} = 6.59 \cdot 10^{-25} \text{ s}$	

Bethe-Bloch

