Particle detection techniques

Introductory notes I

SUMMER INSTITUTE: USING PARTICLE PHYSICS TO UNDERSTAND AND IMAGE THE EARTH 11-21 July 2016
Gran Sasso Science Institute

Gioacchino Ranucci

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.

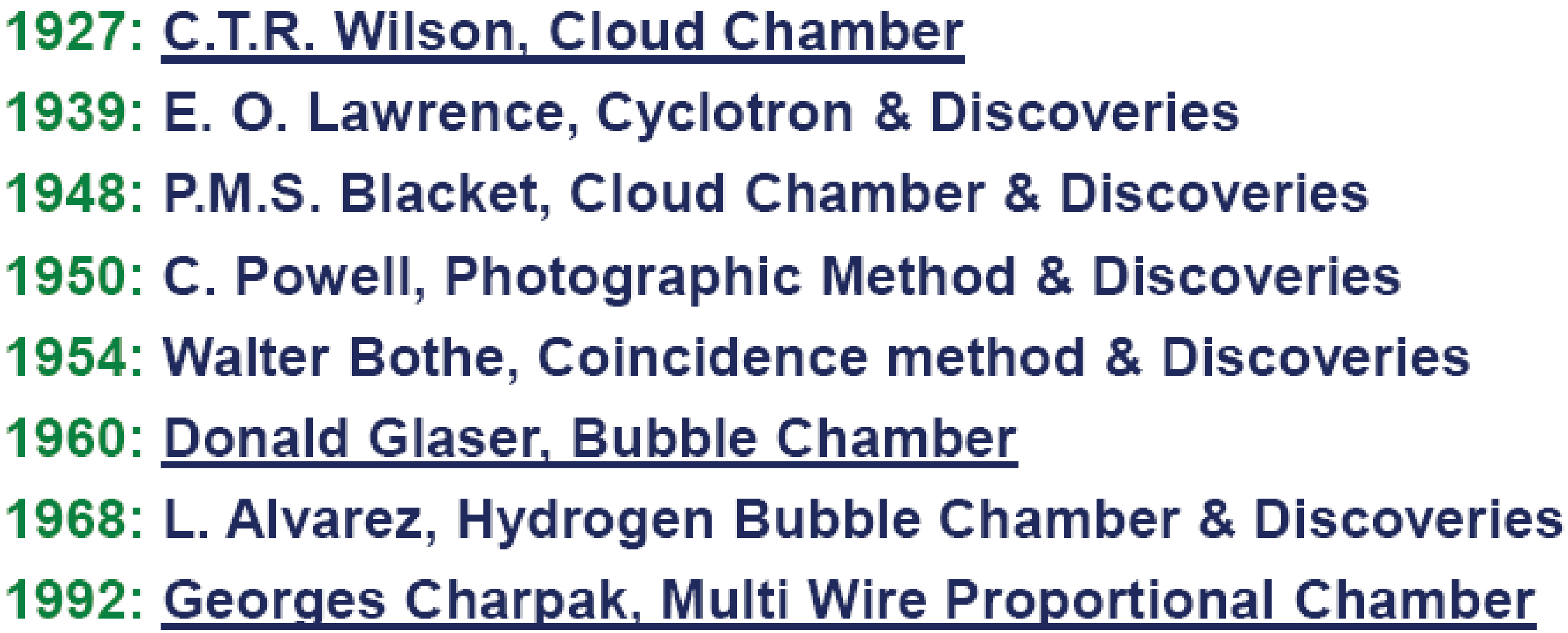
The effect of a concept-driven revolution is to explain old things in new ways.

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 the current experimental horizon

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 Particle?

What is a Detector?

How to detect a particle?

What is a Particle?

The theoretician answer:

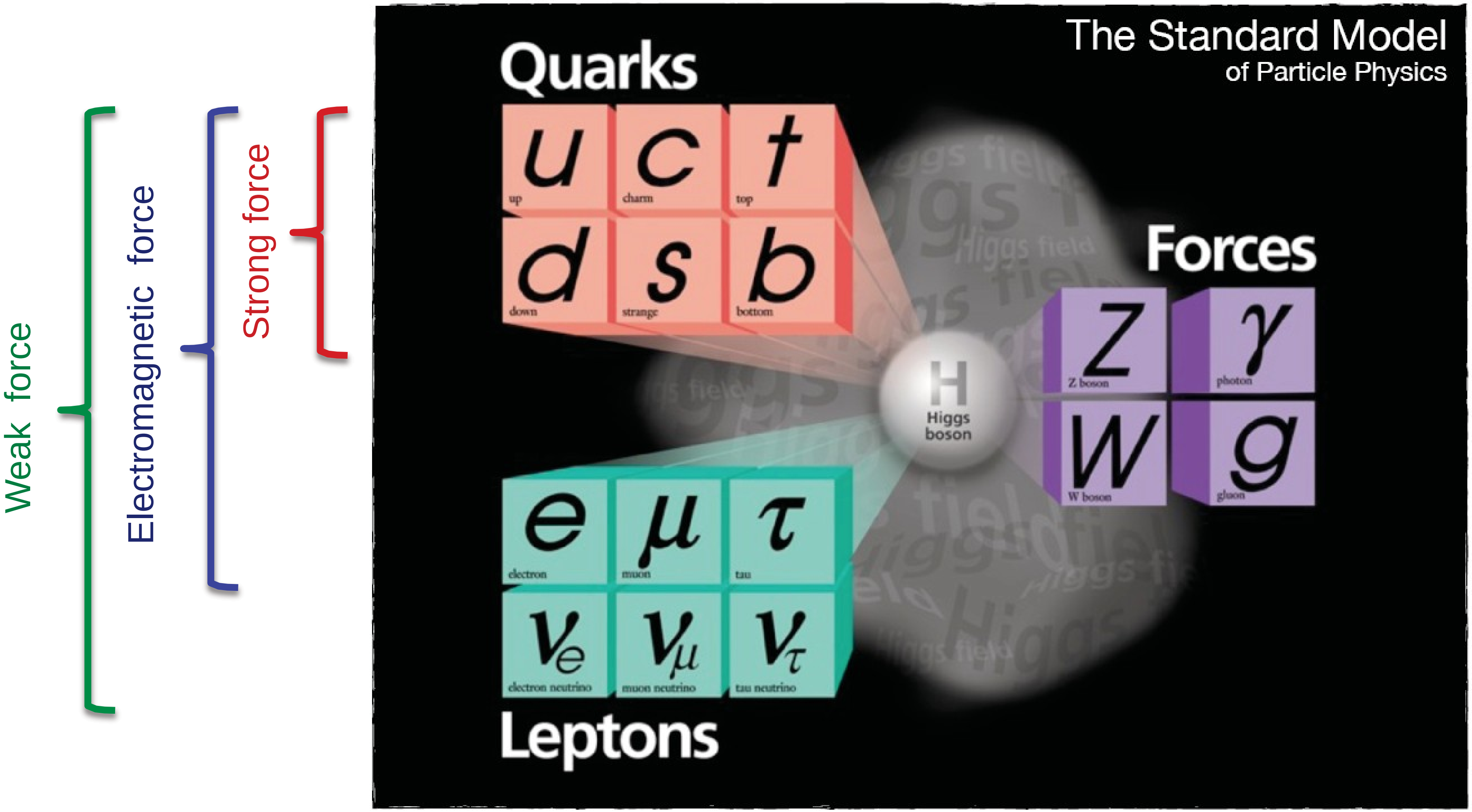
“ a particle is an irreducible representation of the inhomogeneous Lorentz group ”

(E. Wiegner)

That means:

→ Spin 0,1/2, 1, 3/2 & mass>0

What is a Particle?

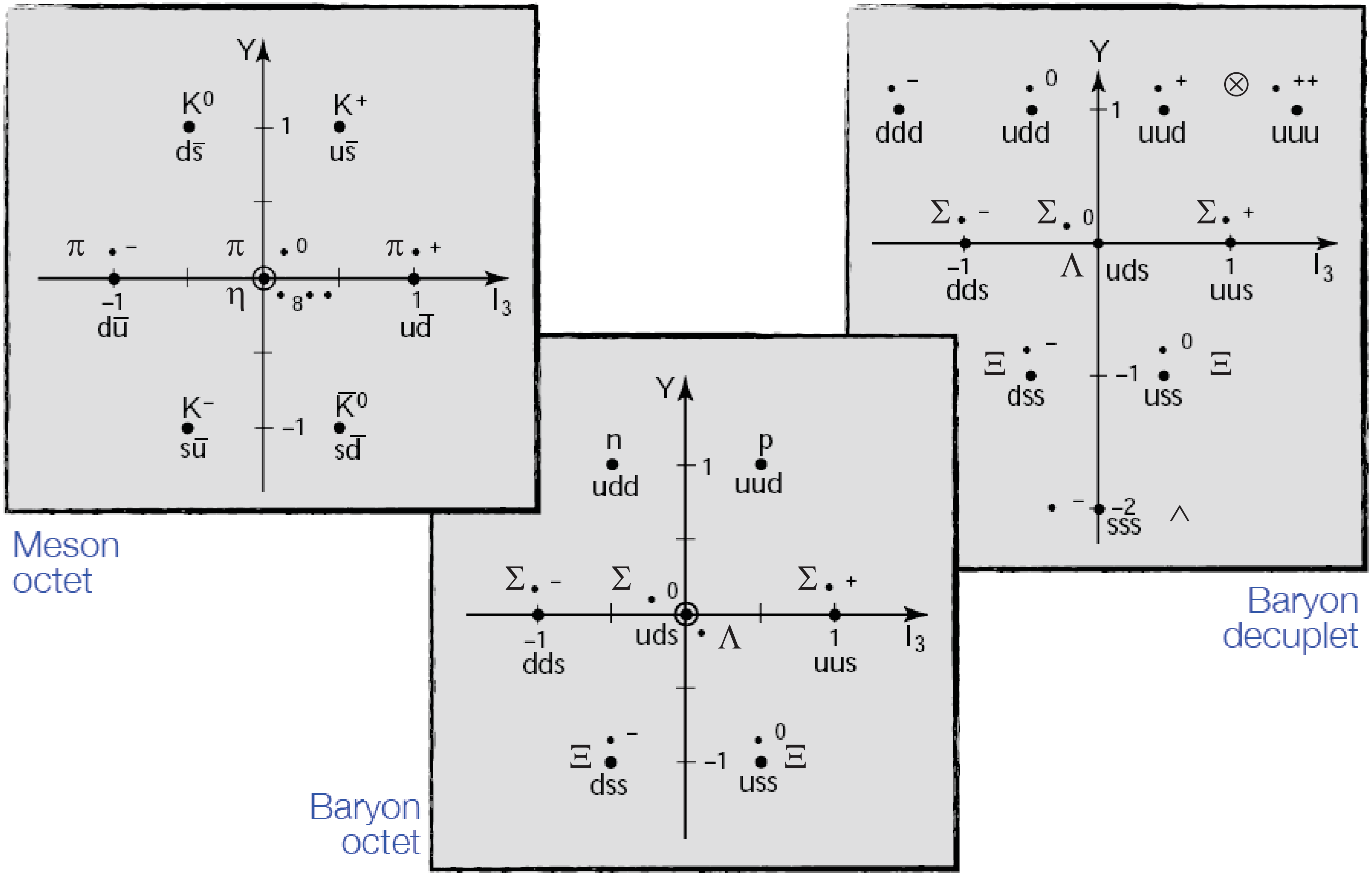


Weak force

Electromagnetic force

Strong force

Barions & mesons

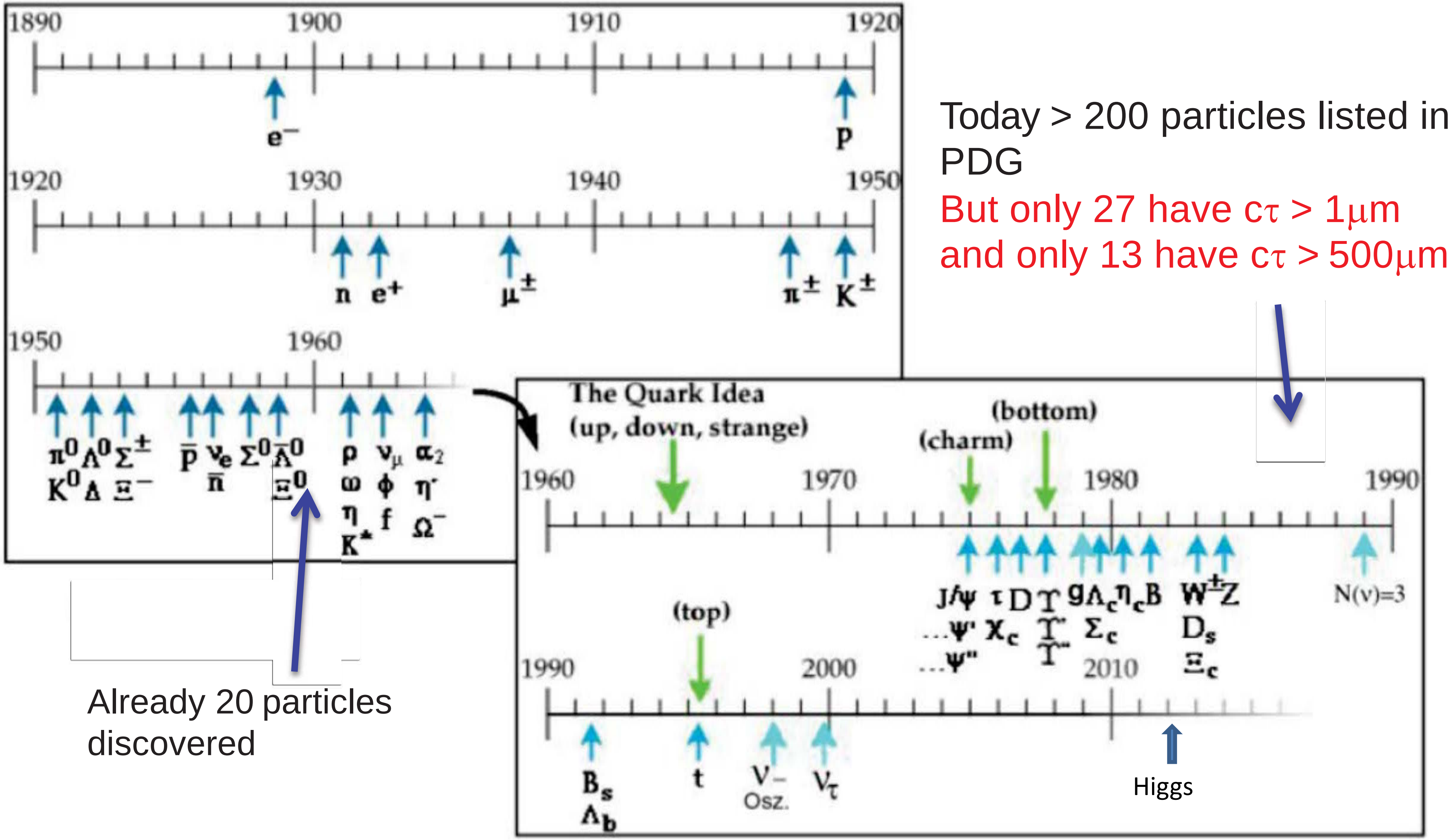


Meson
octet

Baryon
octet

Baryon
decuplet

A history of discoveries



Today > 200 particles listed in PDG

But only 27 have $c\tau > 1\mu m$ and only 13 have $c\tau > 500\mu m$

Already 20 particles discovered

. image and logic discoveries

Particle detection

- The detector sees only ˝stable˝ particles ($c\tau > 500\mu m$)
- 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

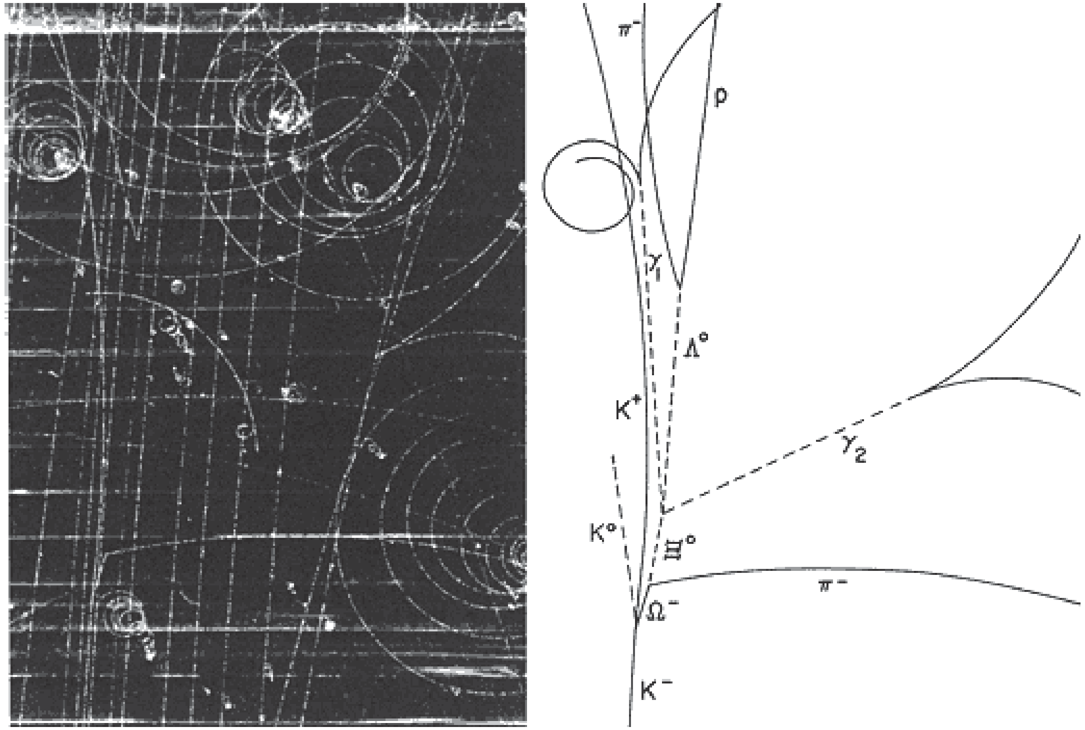
- Neutral particles (photons, neutrons) have to transfer their energy to charged particles to be measured

  →calorimeters

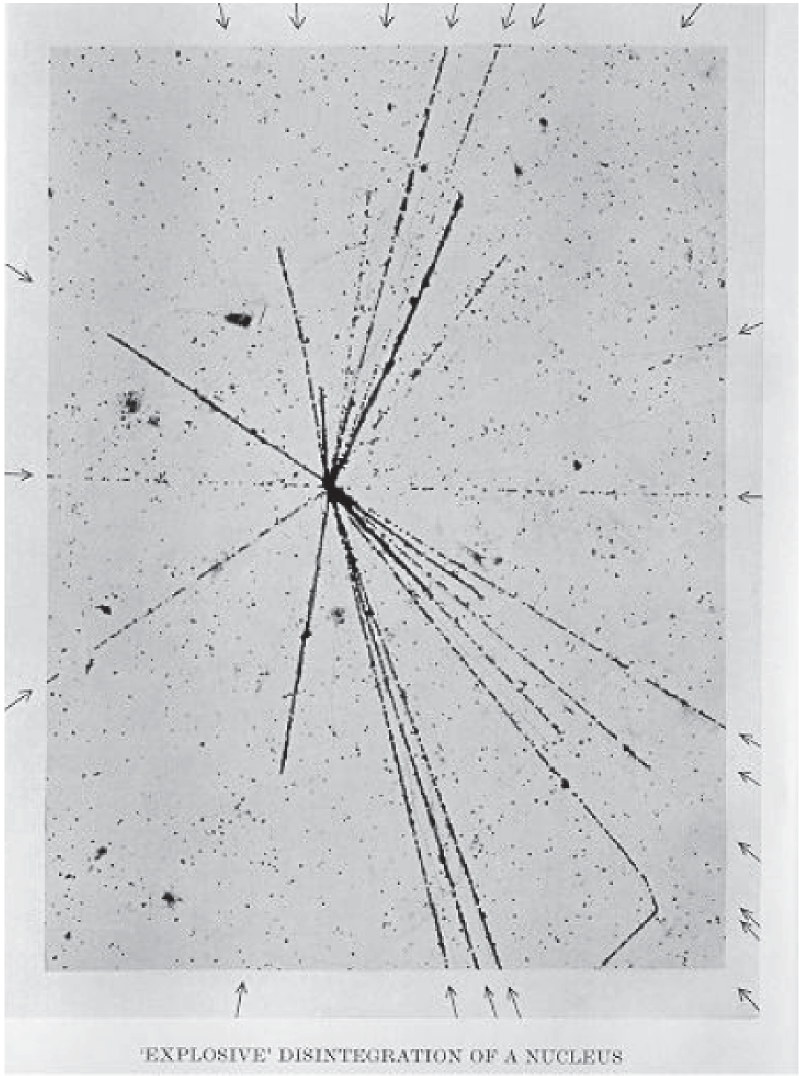
Image tradition

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

- Cloud chambers
- Emulsions
- Bubble chambers

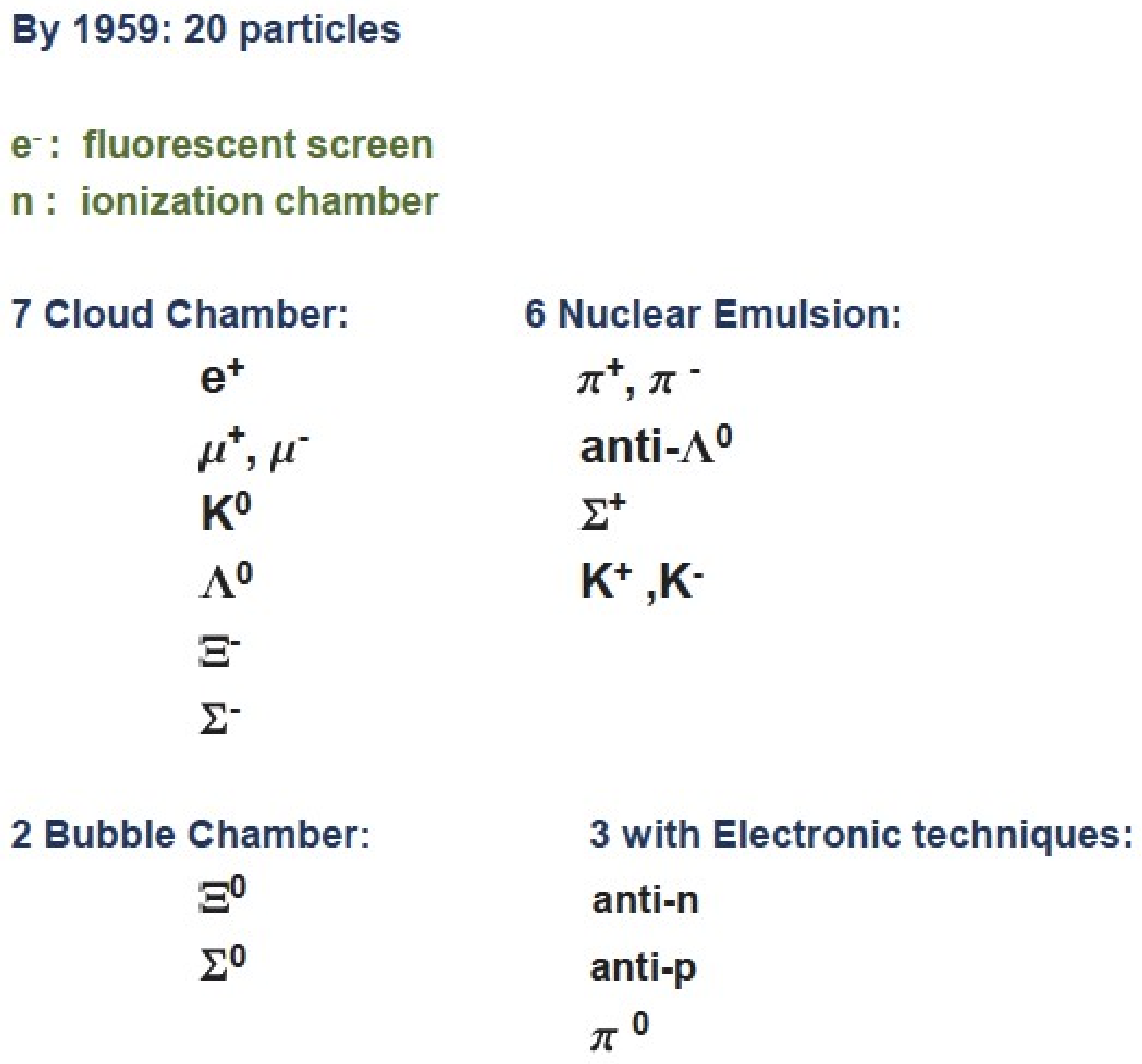


Discovery of the Ω^- in 1964



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^-

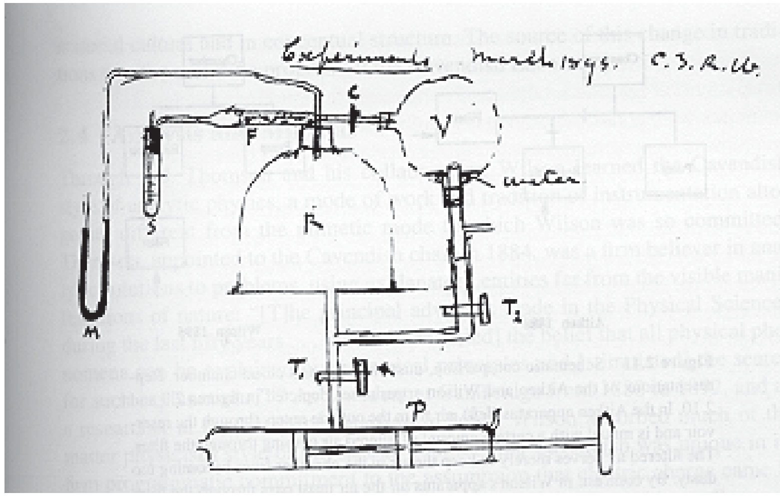
2 Bubble Chamber:

- Ξ^0
- Σ^0

3 with Electronic techniques:

- anti-n
- anti-p
- π^0

The tools of discovery



Cloud chamber, Wilson 1895

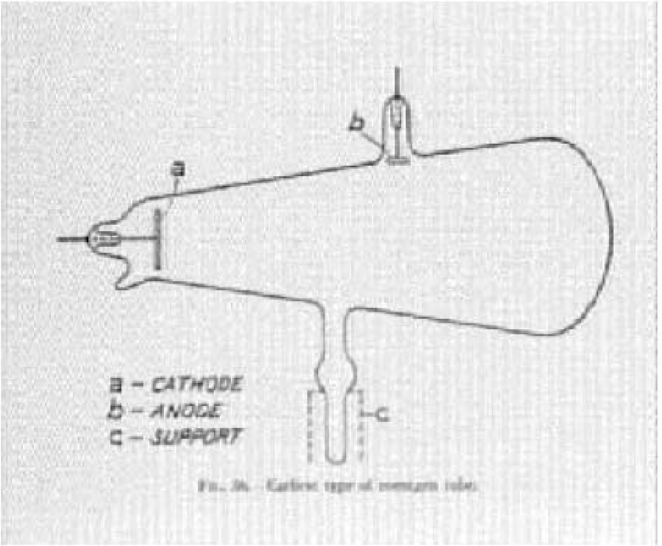
Charles Thomson Rees Wilson, * 1869, Scotland:

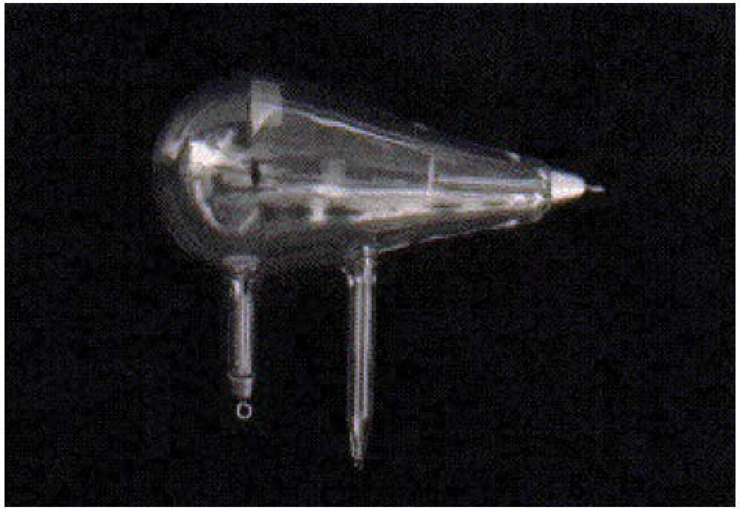
Wilson was a meteorologist who was, among other things, interested in cloud formation initiated by electricity.

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 it's conductivity suggesting that X-rays produced ions in the gas.

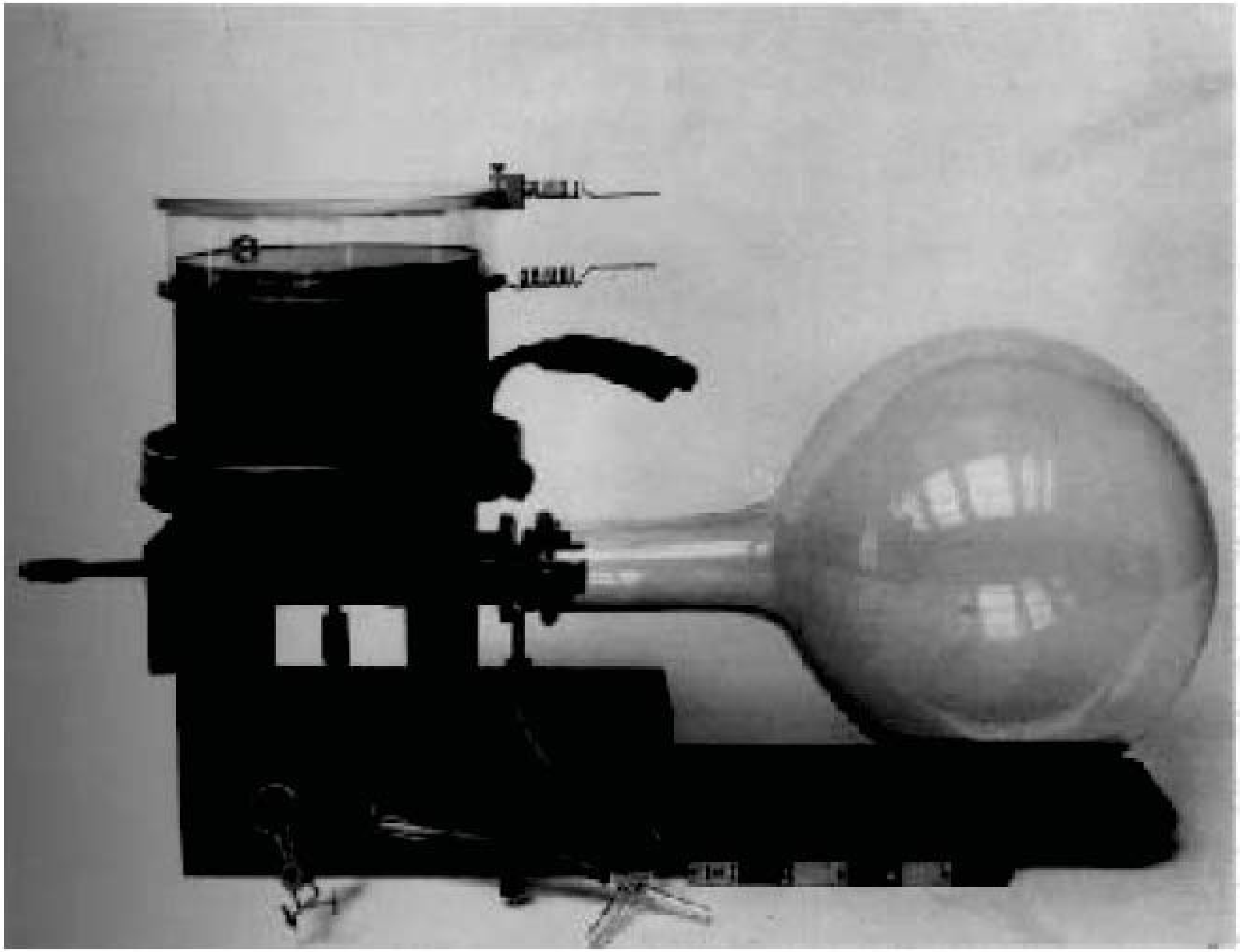
Wilson used an X-Ray tube to irradiate his Chamber and found 'a very great increase in the number of the drops', confirming the hypothesis that ions are cloud formation nuclei.

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).

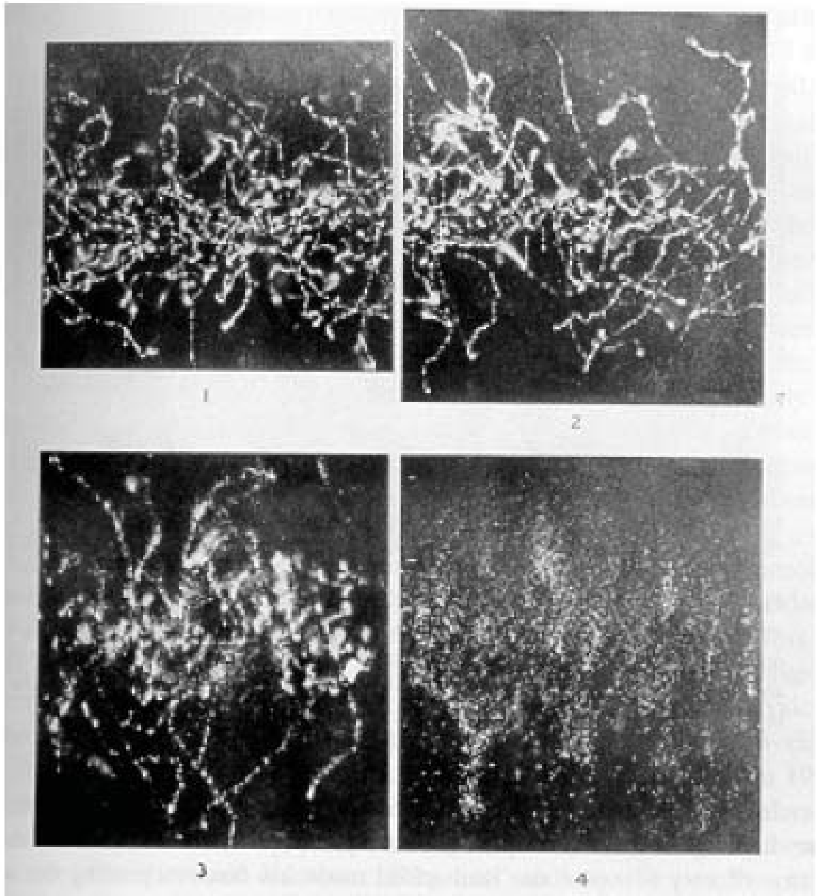
The cloud chamber



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



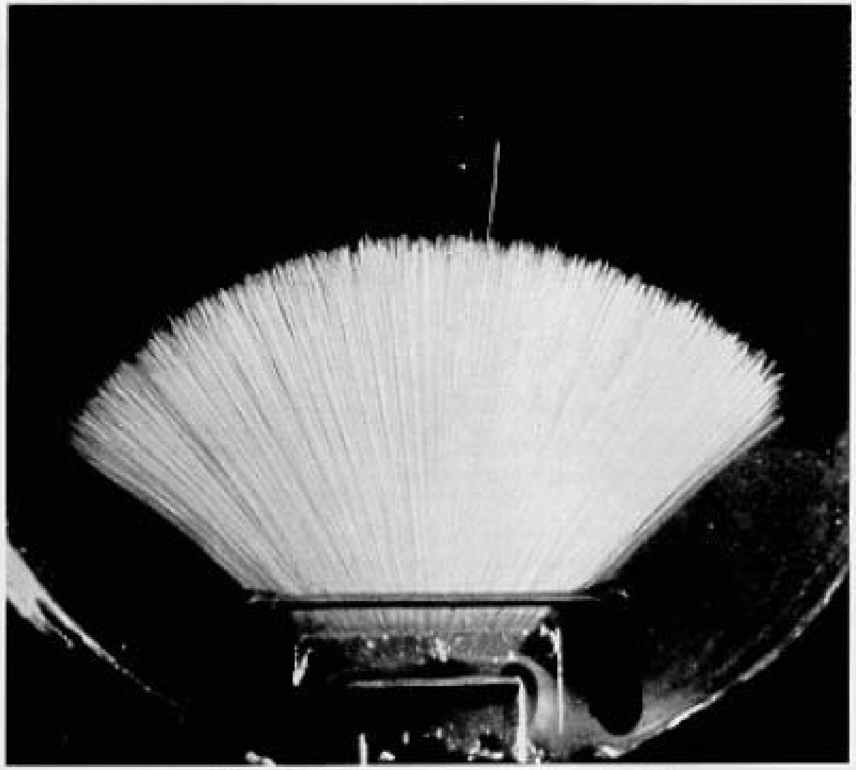


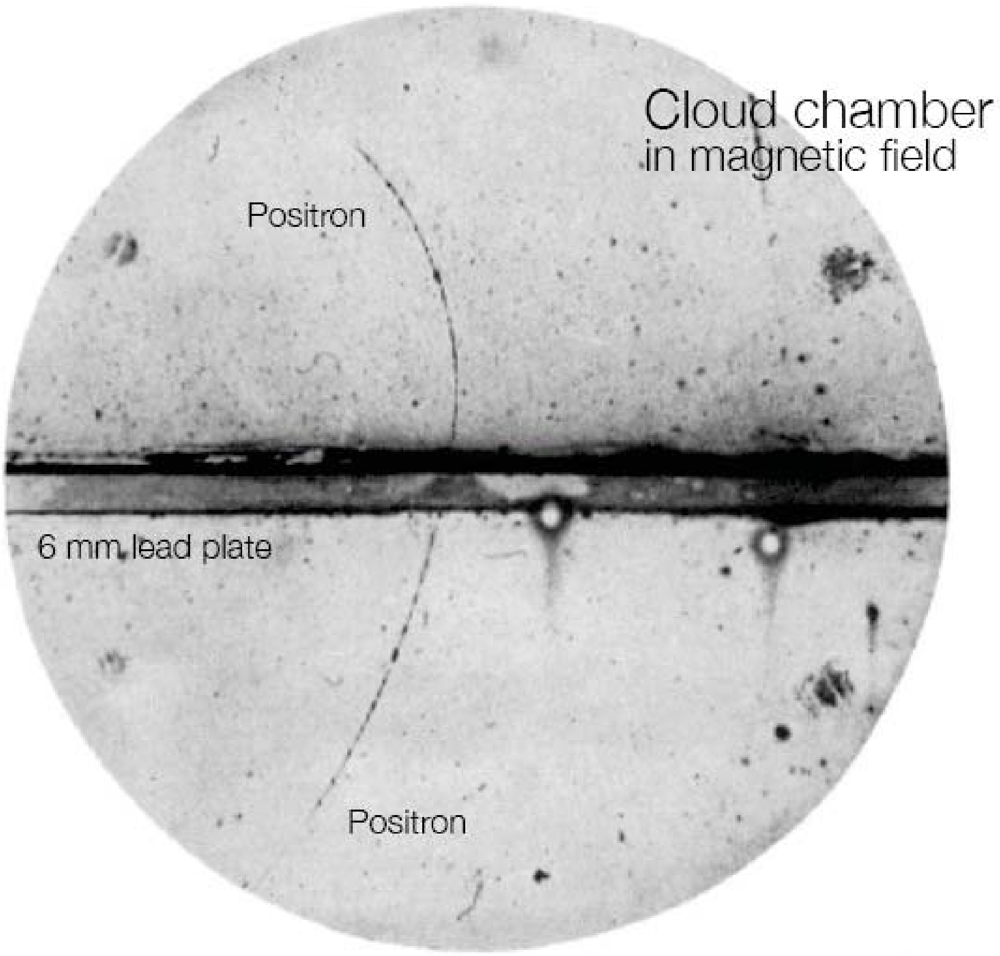
Fig. 13. K. PHILIPP, Naturwiss. 14, 1203 (1926).

X-rays, Wilson 1912

Alphas, Philipp 1926

Important particle discoveries

Positron discovery,
Carl Andersen 1933
[Nobel prize 1936]

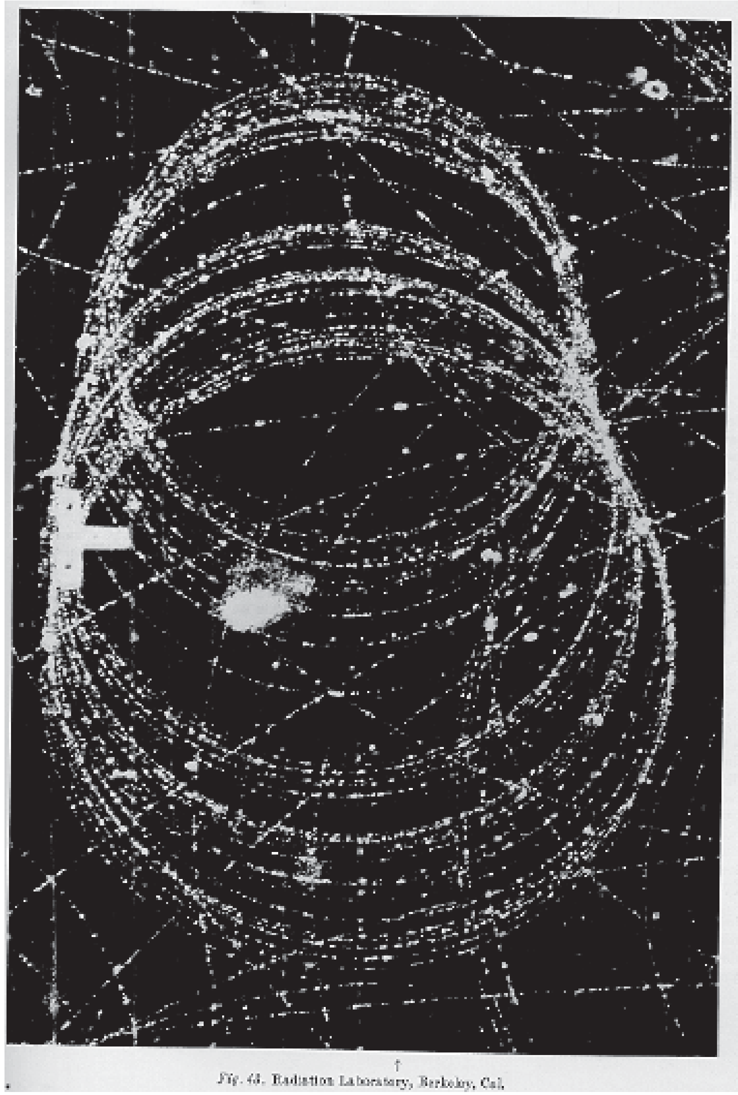


Magnetic field 15000 Gauss, chamber diameter 15cm.

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 and 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 cause in part by Bremsstrahlung.
The curvature indeed shows sudden changes as can most clearly be seen at about the seventeenth circle.

Fast electron in a magnetic field at the Bevatron, 1940

Important particle discoveries

Discovery of the pion
Nuclear emulsion technique

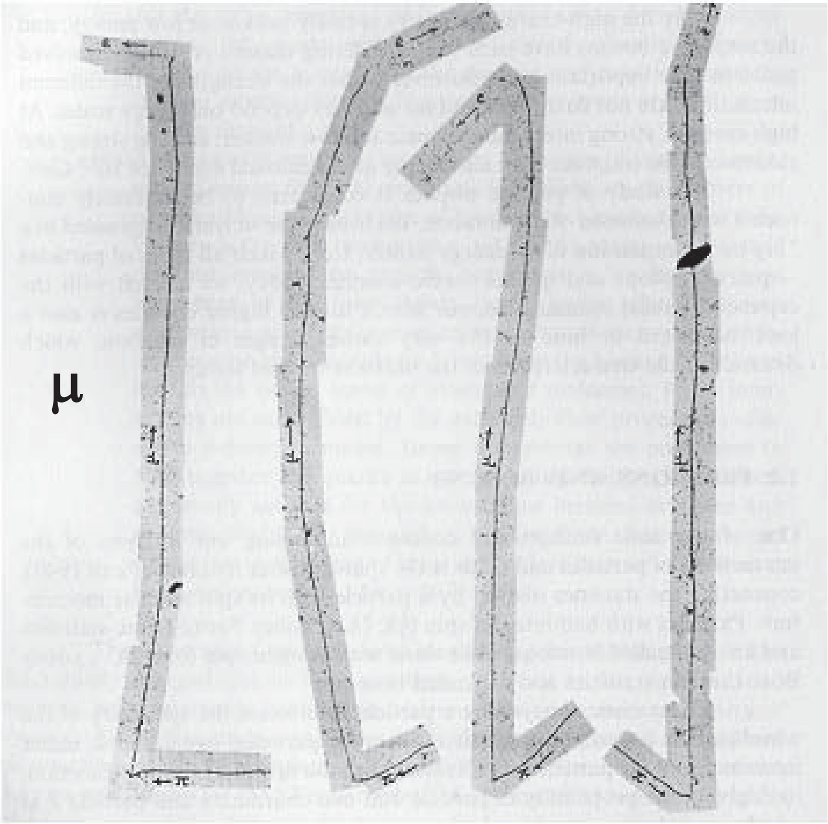
[Powell 1947; Nobel prize 1950]

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.



$$\pi \rightarrow \mu^- \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Intermezzo: why do we see muons on Earth?

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

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

$s = v\,\tau = 600$ m →no muon should reach Earth!

But we see them .

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

$s = v\,\gamma\tau = 12.5$ km →can reach Earth!

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

$s = v\,\gamma\tau = 115$ m →very rare on Earth

→Discovered in emulsion experiments on high mountains

Intermezzo: energy spectrum of 2-bodies decay

$\pi \rightarrow \mu^- \; \nu_\mu$

$\tau_\pi = 2.6 \; 10^{-8}$ s

Initial
$p = 0$,
$E = m_\pi c^2$

Final
$p_1 + p_2 = 0$
$E_1 + E_2 = E$

2 unknown in 2 equations →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

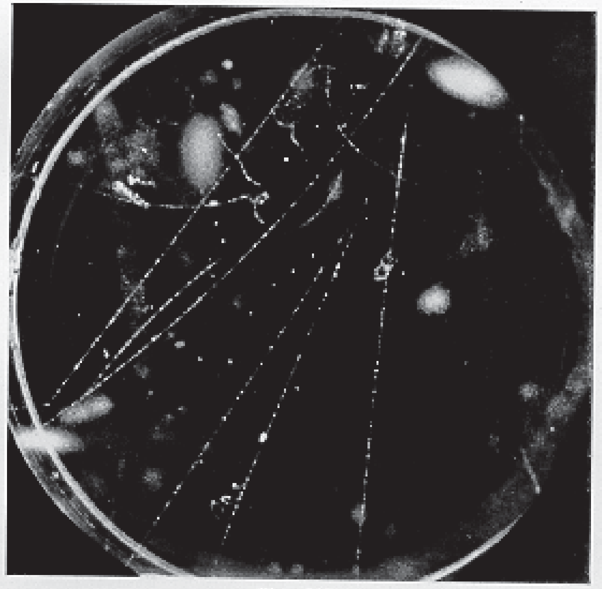


Plate 115

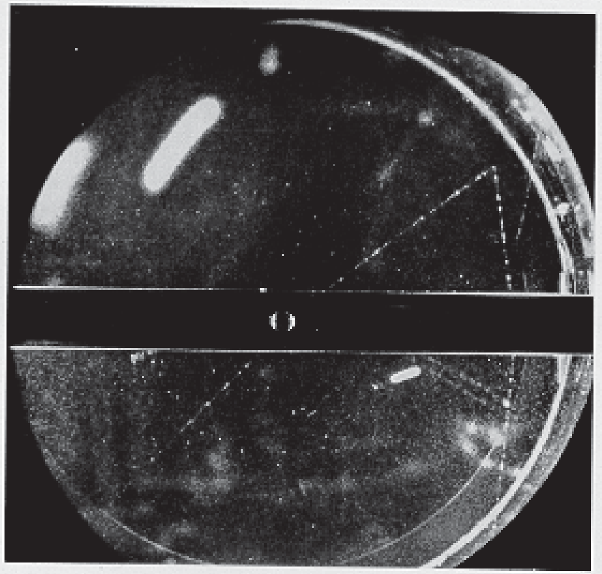


Plate 116

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+-0.3 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 on 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 1000m_e . ’

Rochester and Wilson

From image to electronic detectors

- With the latest bubble chambers position resolution ~5 μm
- Best reconstruction of complex decays

- But low rate capability ~ few tens / second (LHC ~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
  - Silicon detectors

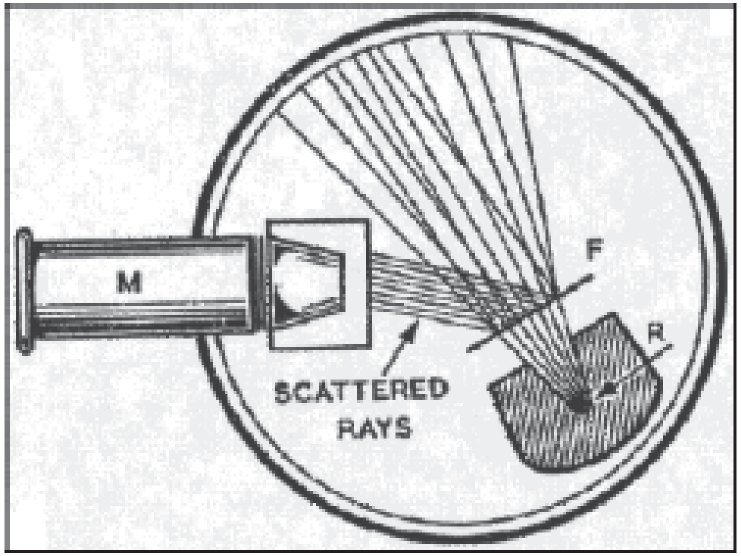
Logic (electronic) tradition

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

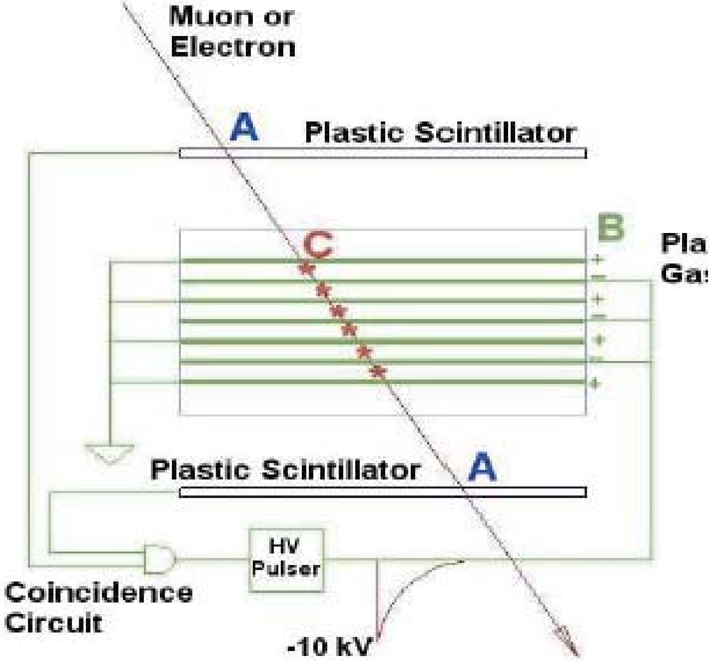
Scintillating Screen:

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



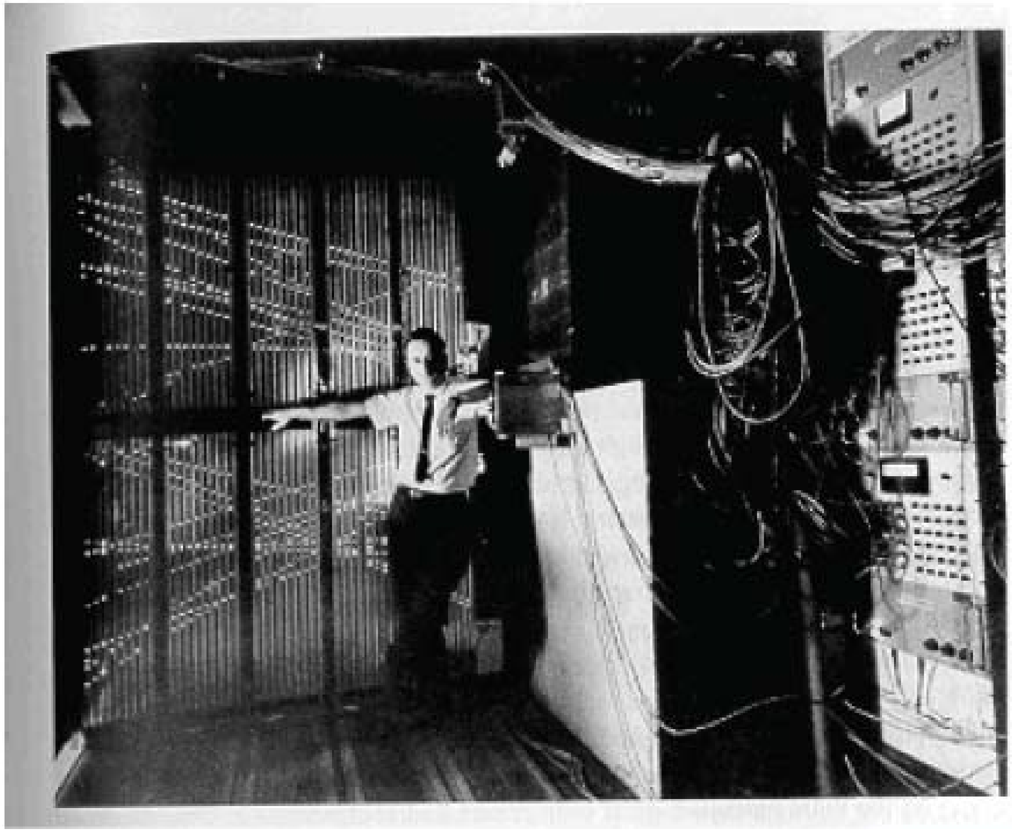
A charged particle traverses the detector and leaves an ionization trail.

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

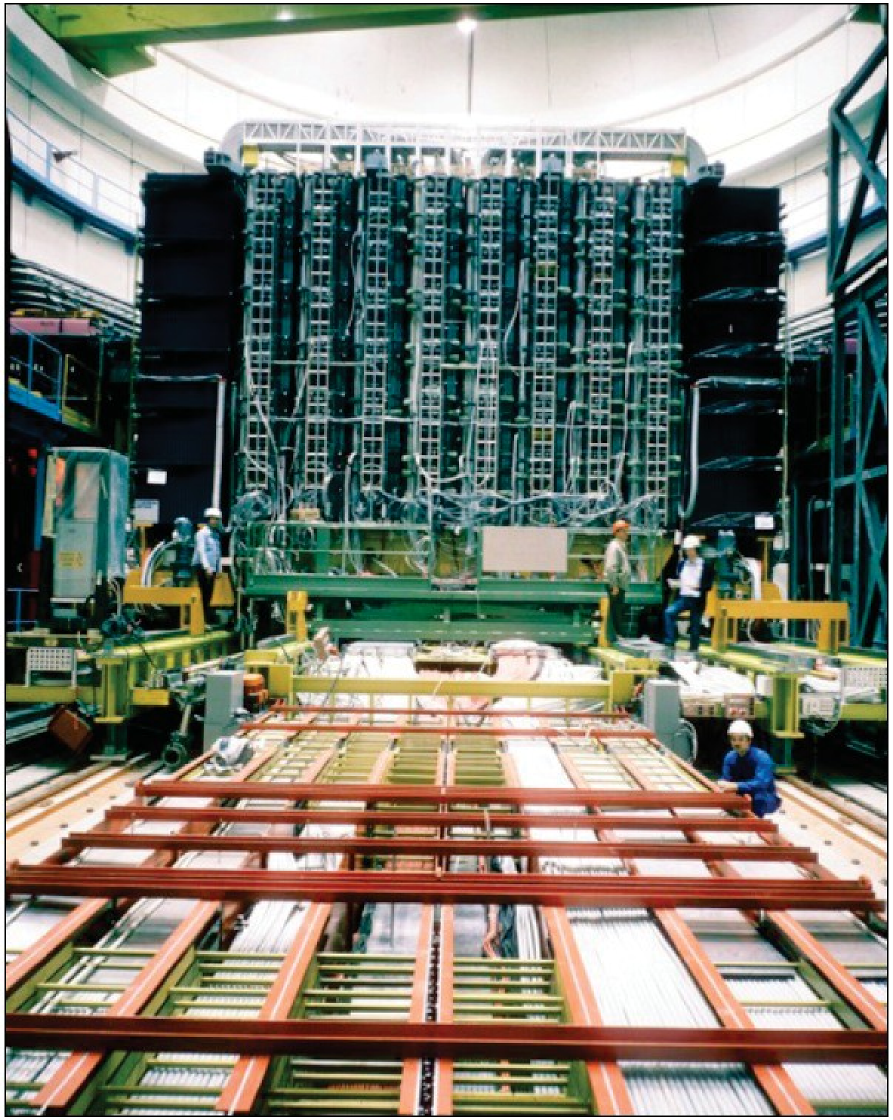
The Spark Chamber was developed in the early 60ies.

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.



The merge of Electronic Images



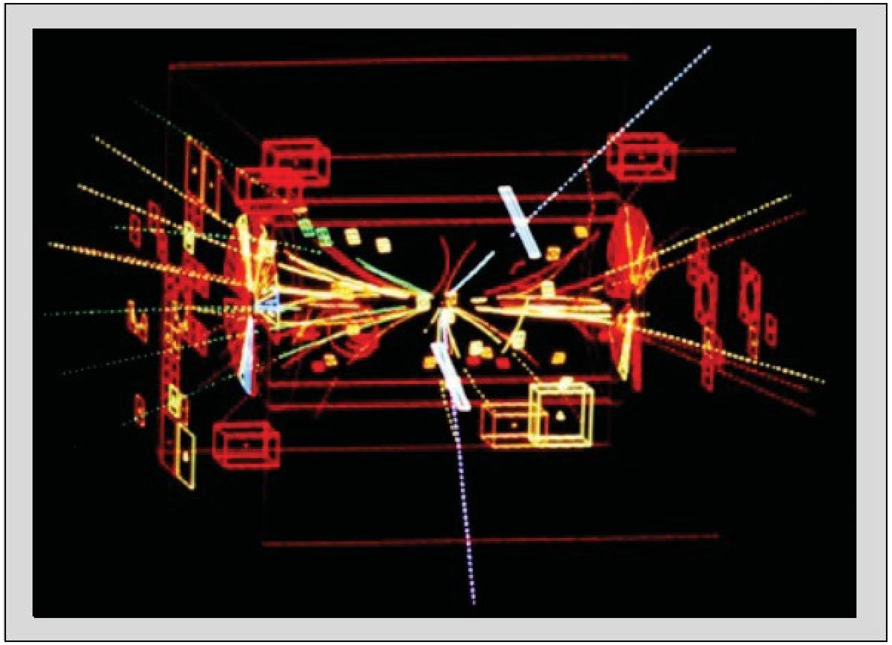
UA1
Detector

Discovery of the
W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

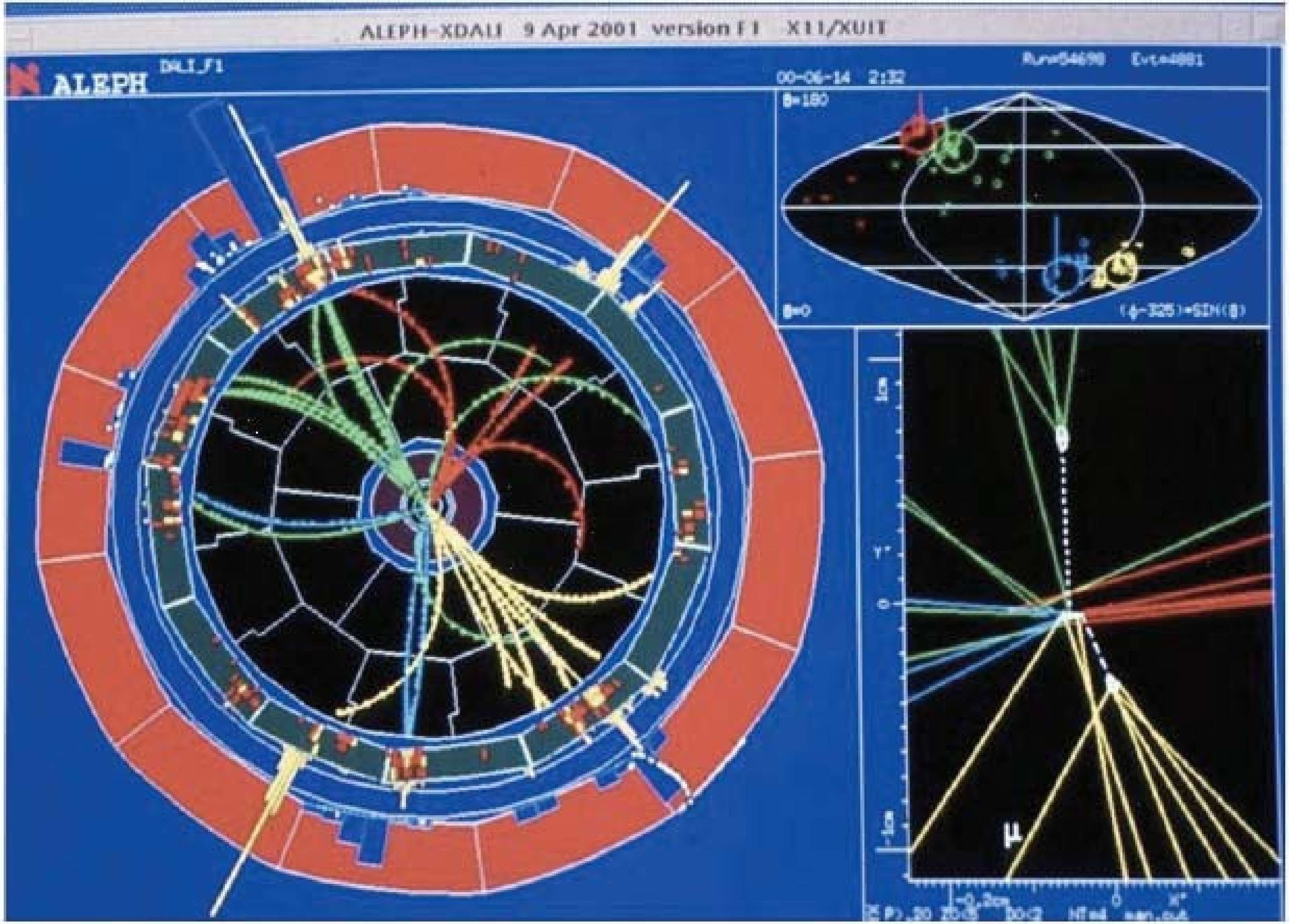
First Z^0 particle seen by UA1



$Z_0 \rightarrow e^+e^-$

LEP 1988 - 2000

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

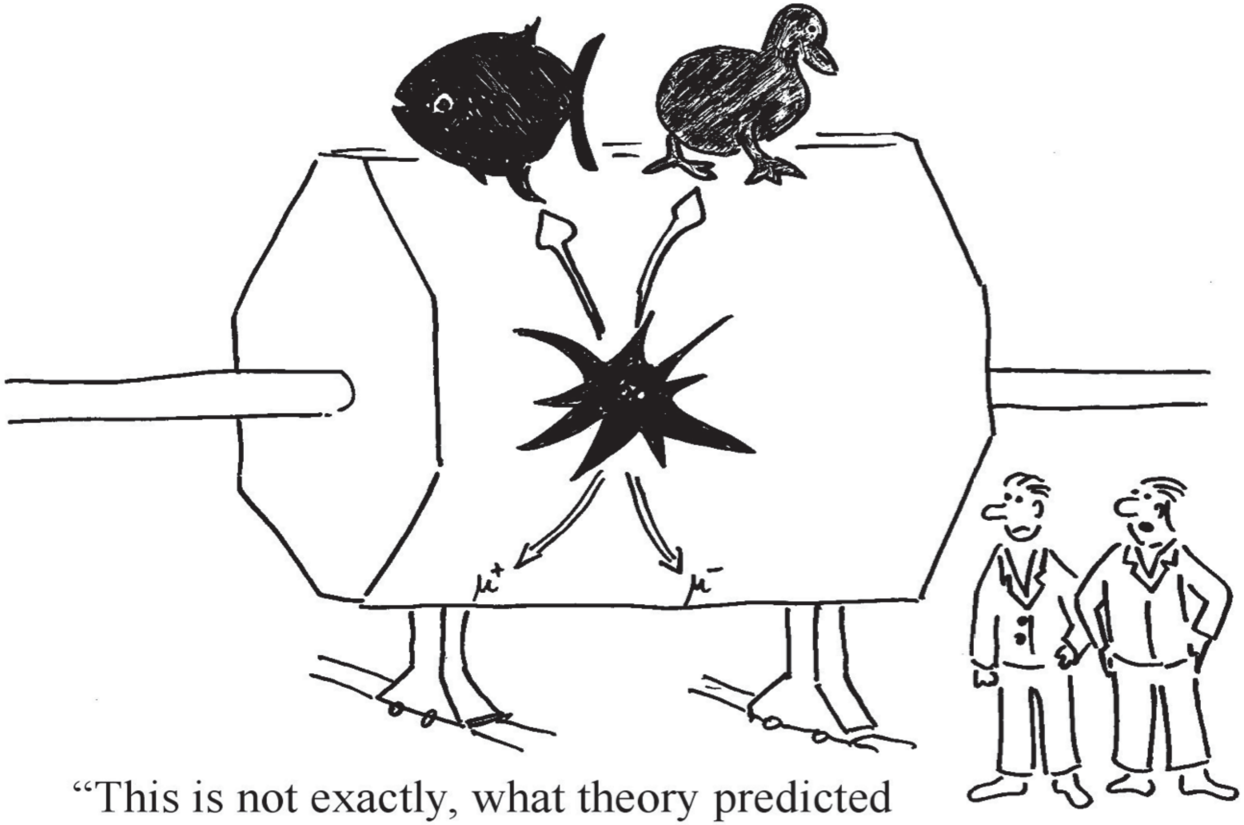


Important particle discoveries … continue

Discovery of the Higgs boson (2012)

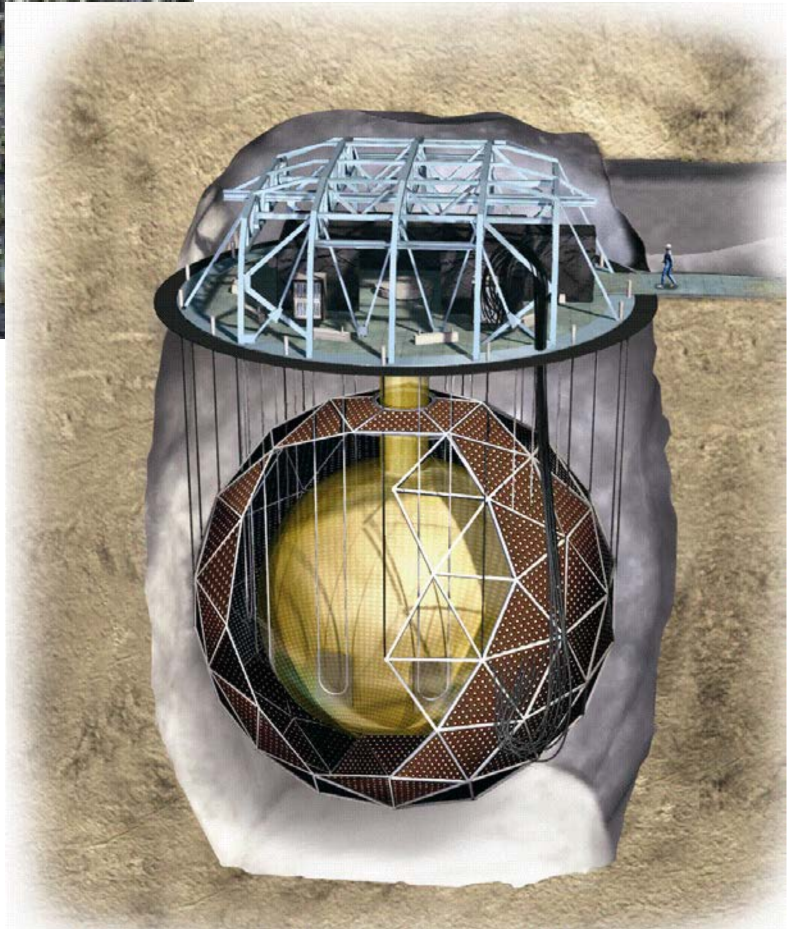
ATLAS and CMS collaborations

[P. Higgs, F. Englert, Nobel 2013]



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

Super-Kamiokande



The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

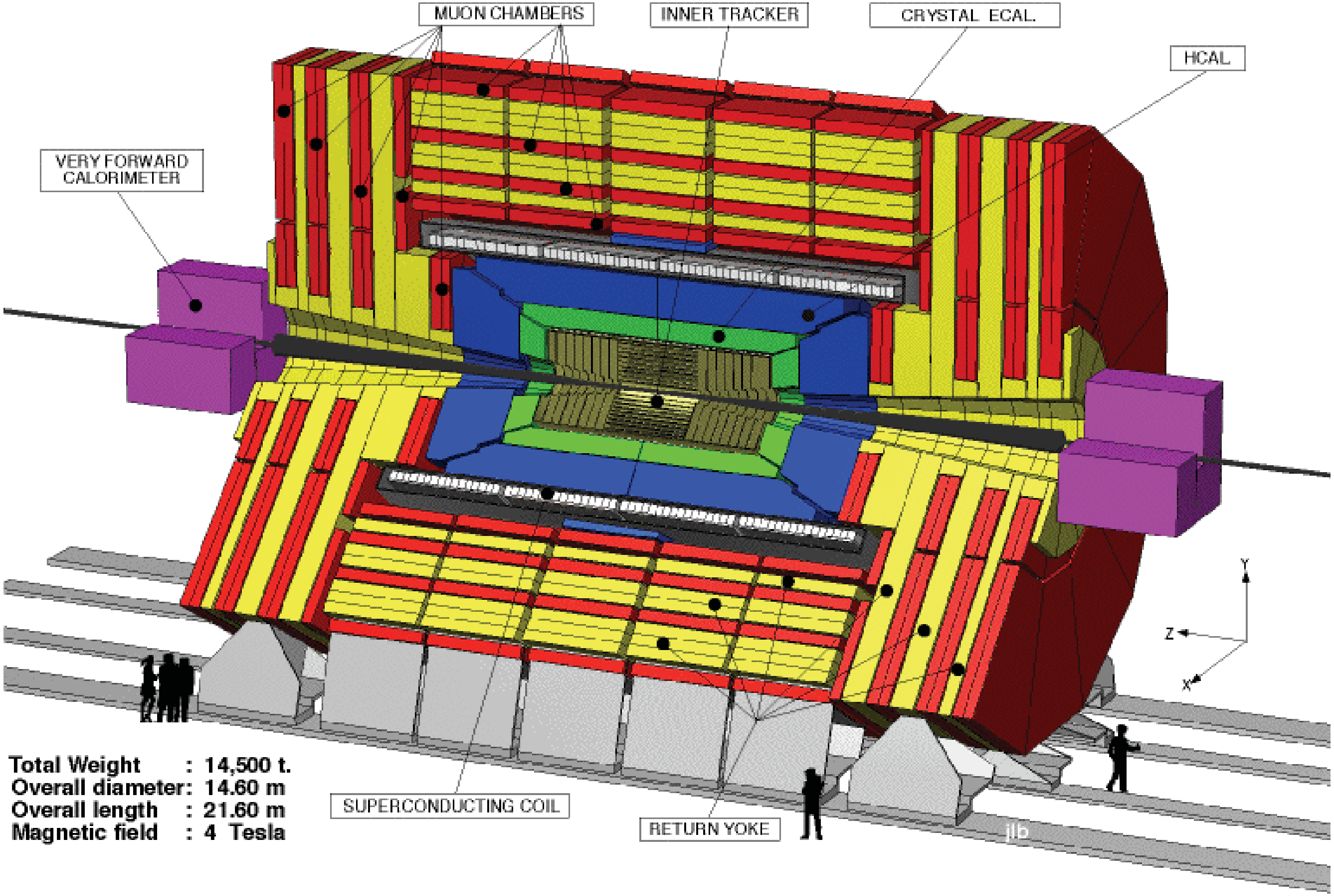
Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

SNO

Discovery of neutrino oscillations

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



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

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:		Type of detection principle:
- position and direction	$x,\ \vec{x}$	position and tracking
- momentum	$\lvert\vec{p}\rvert$	tracking in a magnetic field
- energy	E	calorimetry
- mass	m	Spectroscopy and PID
- velocity	β	Cherenkov radiation or time of flight
- transition radiation	γ	TRD
- spin, lifetime		

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

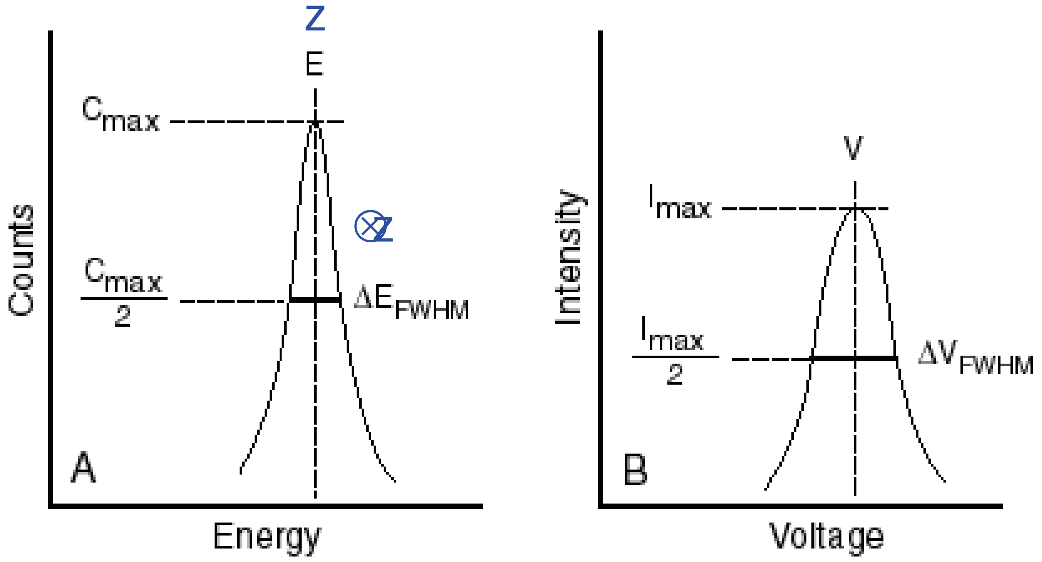
with which resolution?

- 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:



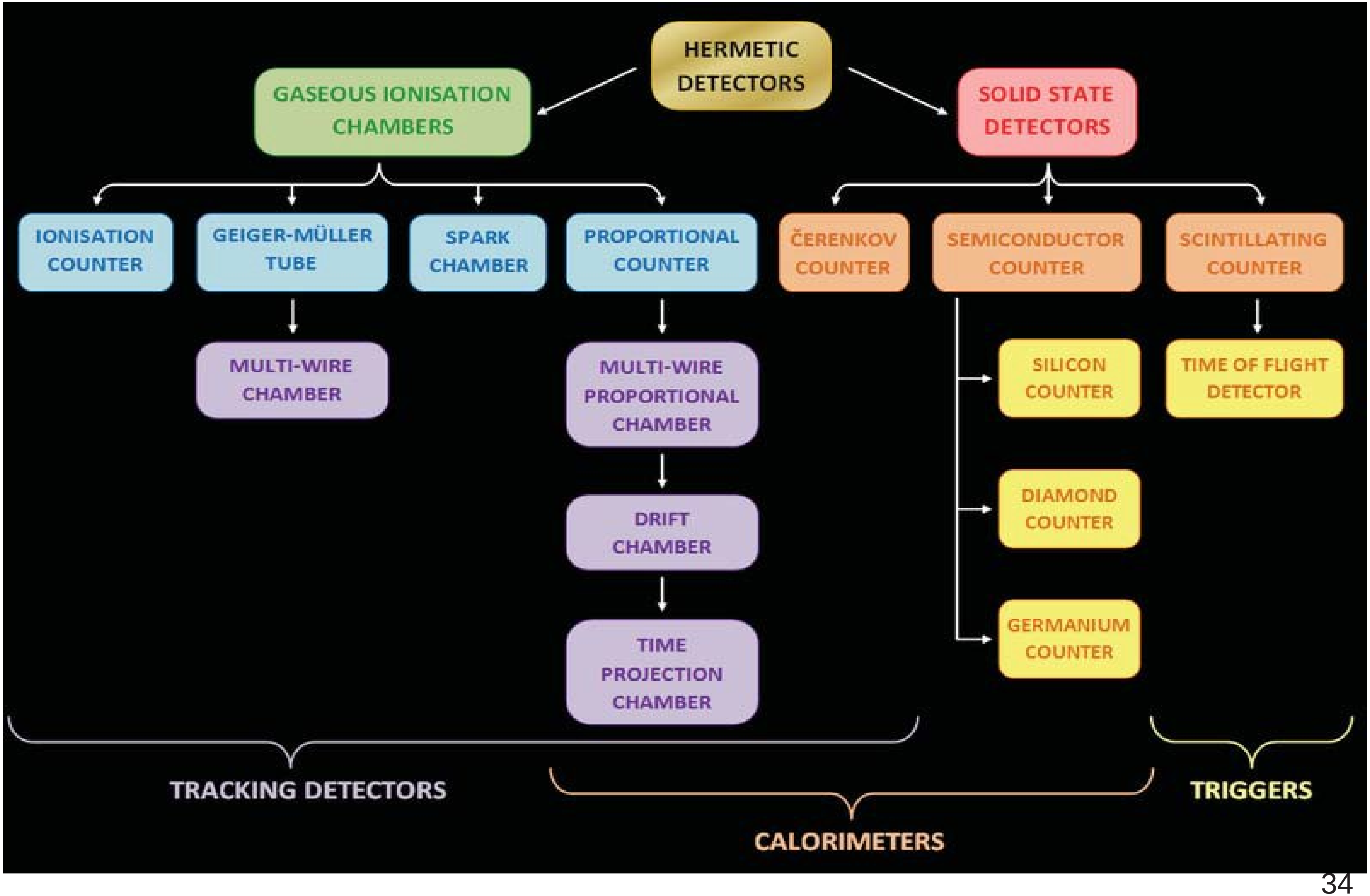
$$\boxed{\frac{\sigma_z}{\langle z \rangle} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}}$$

→Lowest limit for the resolution apart from Fano factor correction

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)

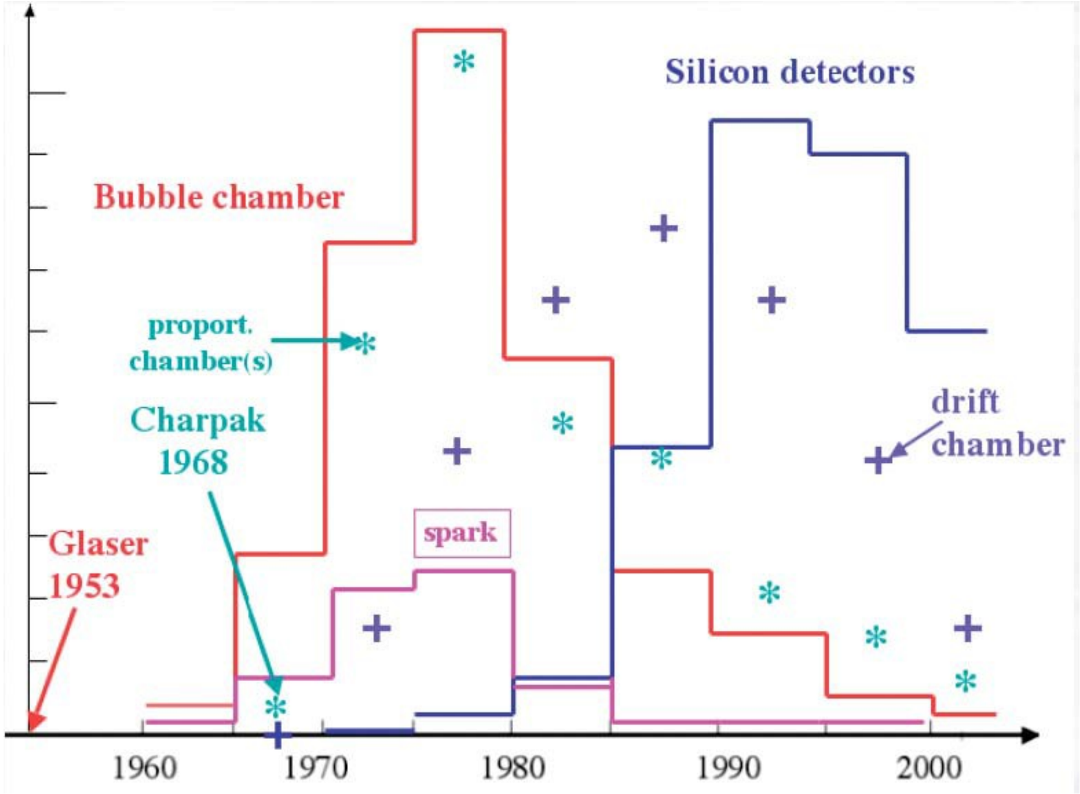
•**Cloud Chambers** dominating until the 1950s
→ Now very popular in public exhibitions related to particle physics

• **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

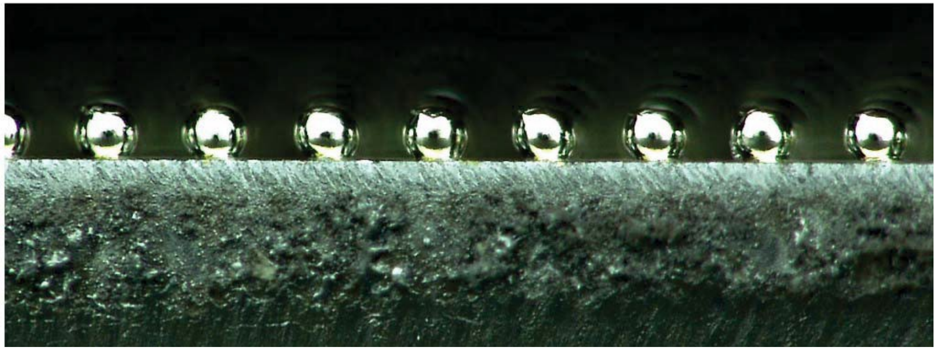
•**Wire Chambers** (MWPCs and drift chambers) started to dominate since 1980s

•Since early 1990s solid **state detectors** are in use started as small sized vertex detectors
→ now ~200 m^2 silicon surface in CMS tracker

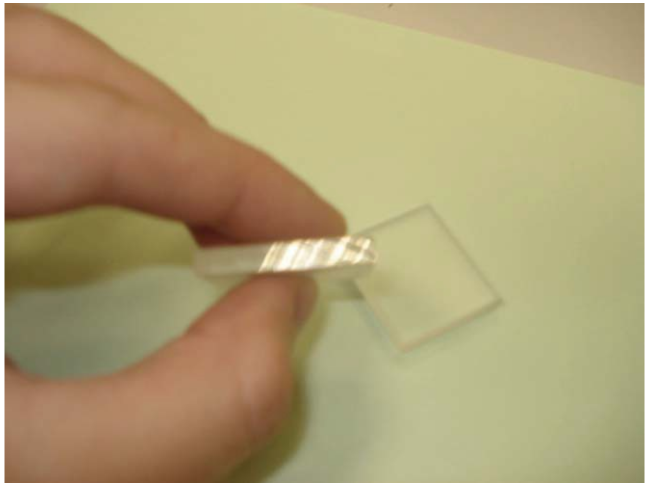
- Scintillators and water Cerenkov detectors in ν physics



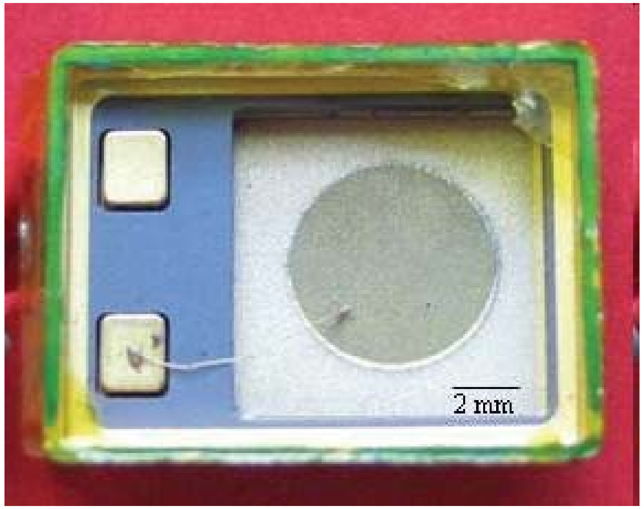
Bright innovations in the future



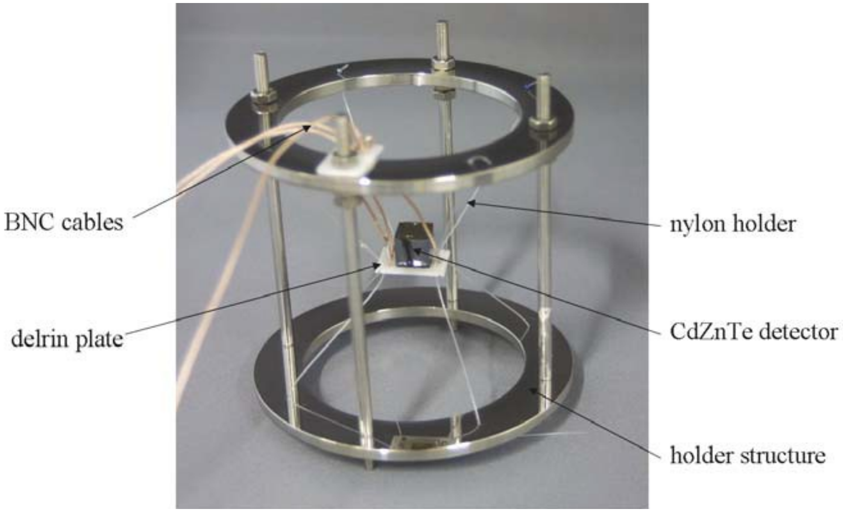
Gold bump bonding



Sapphire as calorimeter



Diamond as beam monitor and future Pixel detector

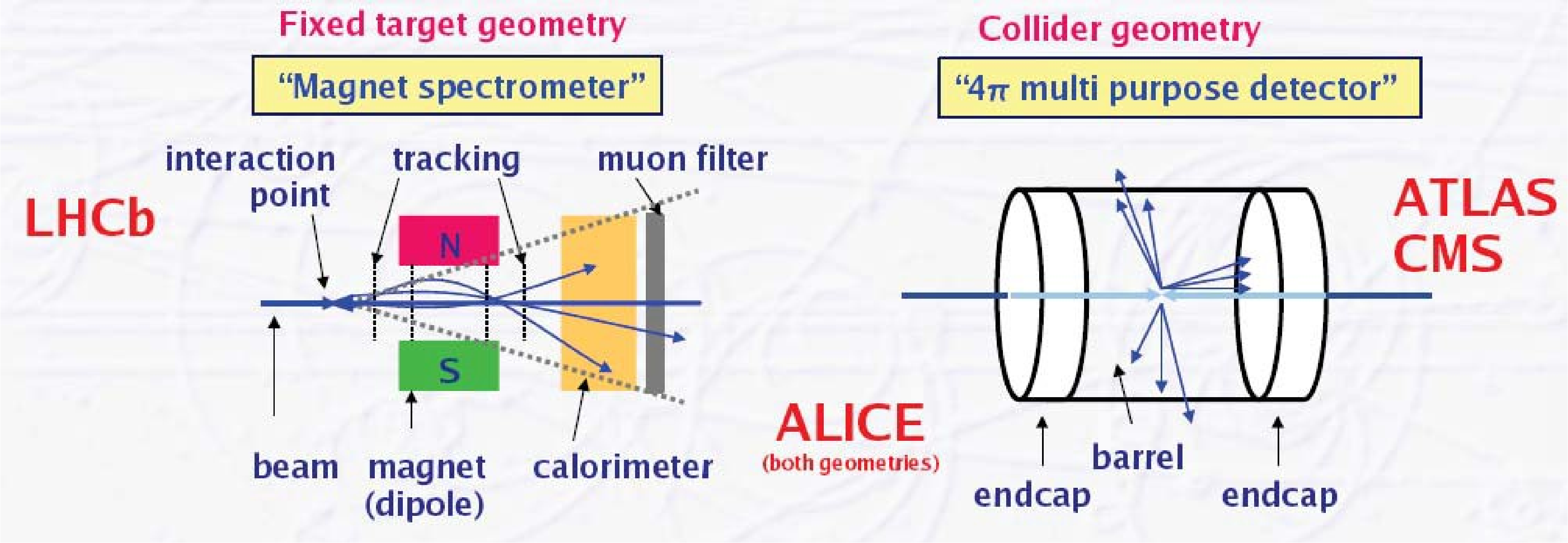


Cadmium zinc telluride bolometers for neutrino-less double beta decay

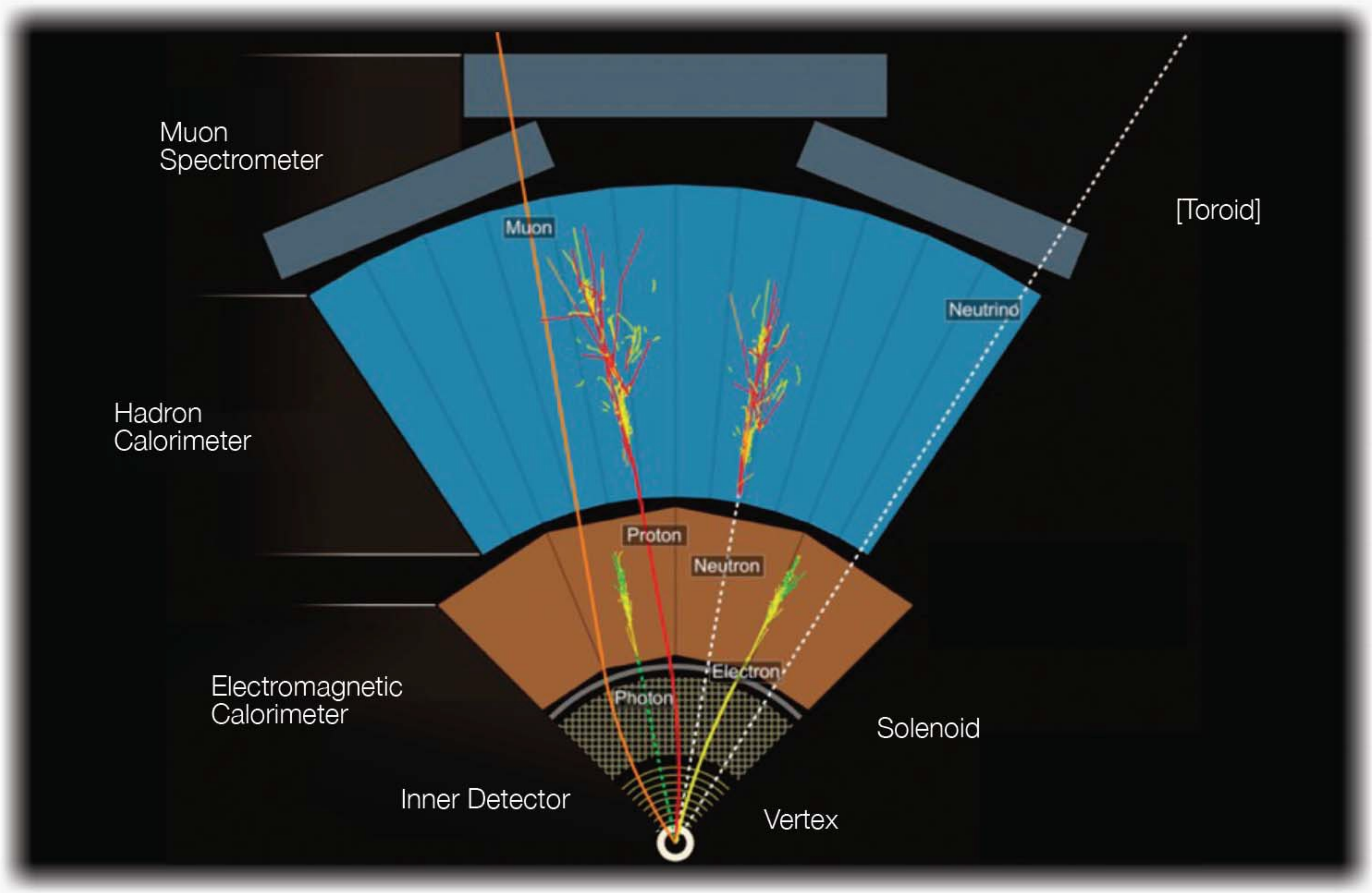
HEP detectors

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

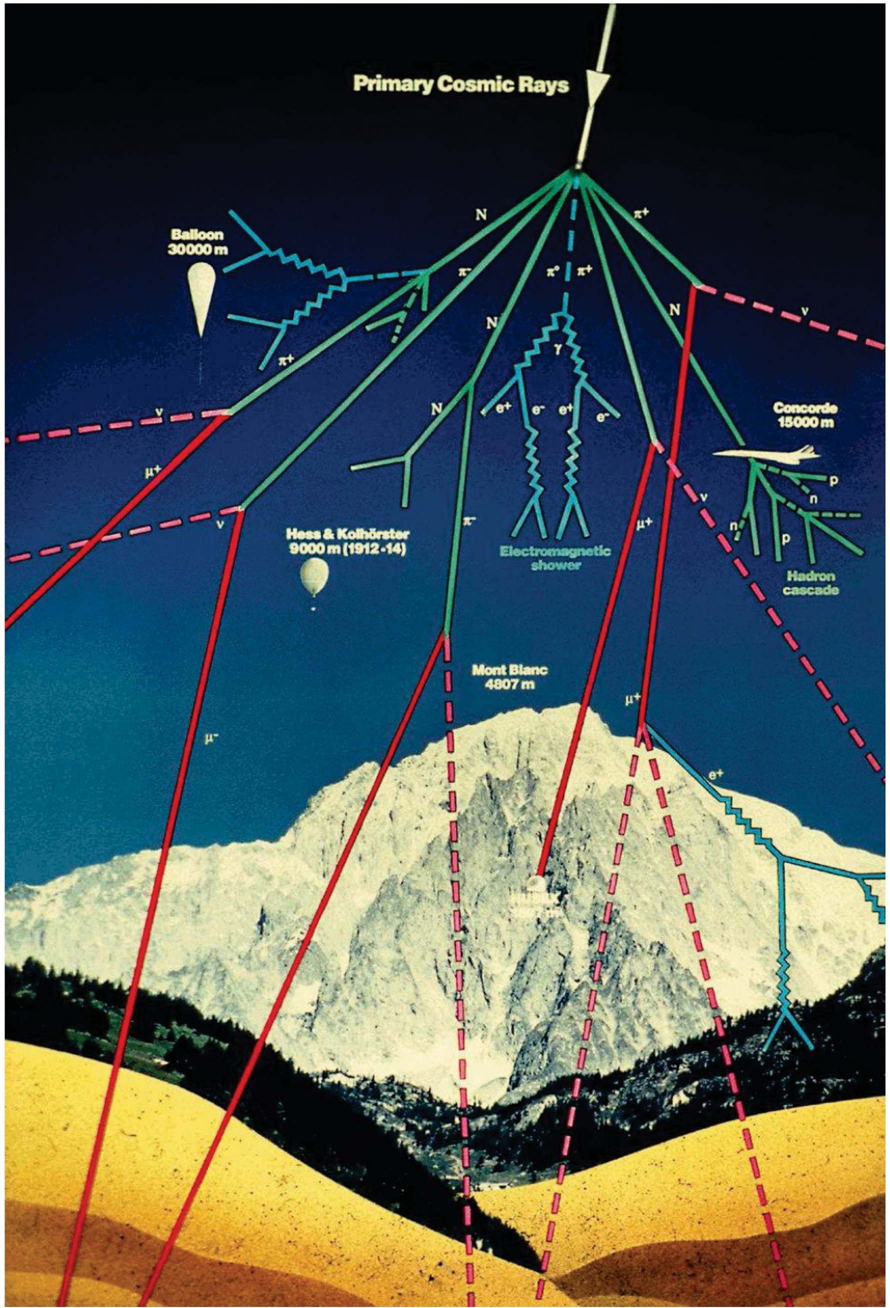
Efficiency: not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, electronics, mechanics)



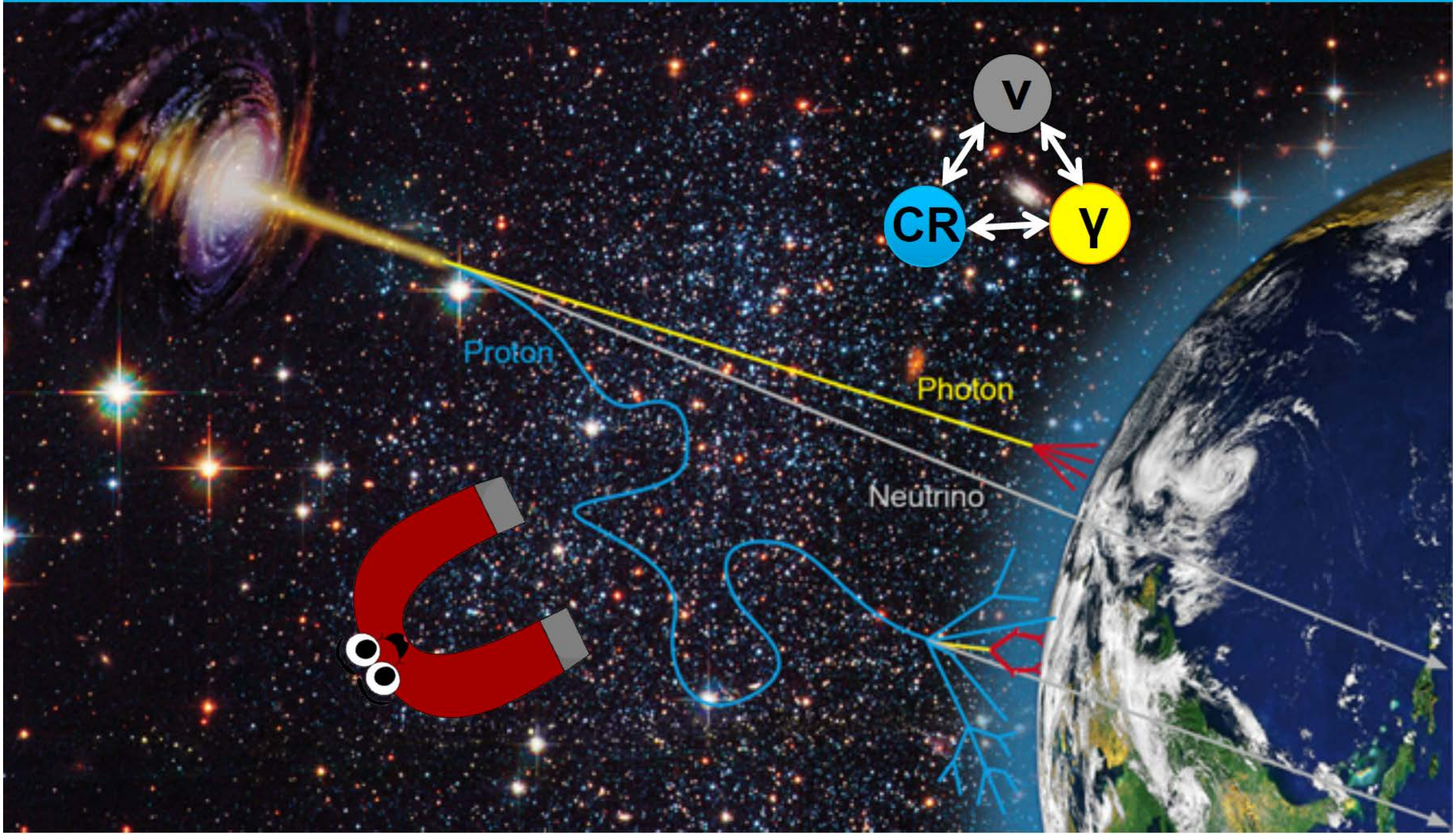
Particle detector: detector system @ colliders



Astro-particle physics

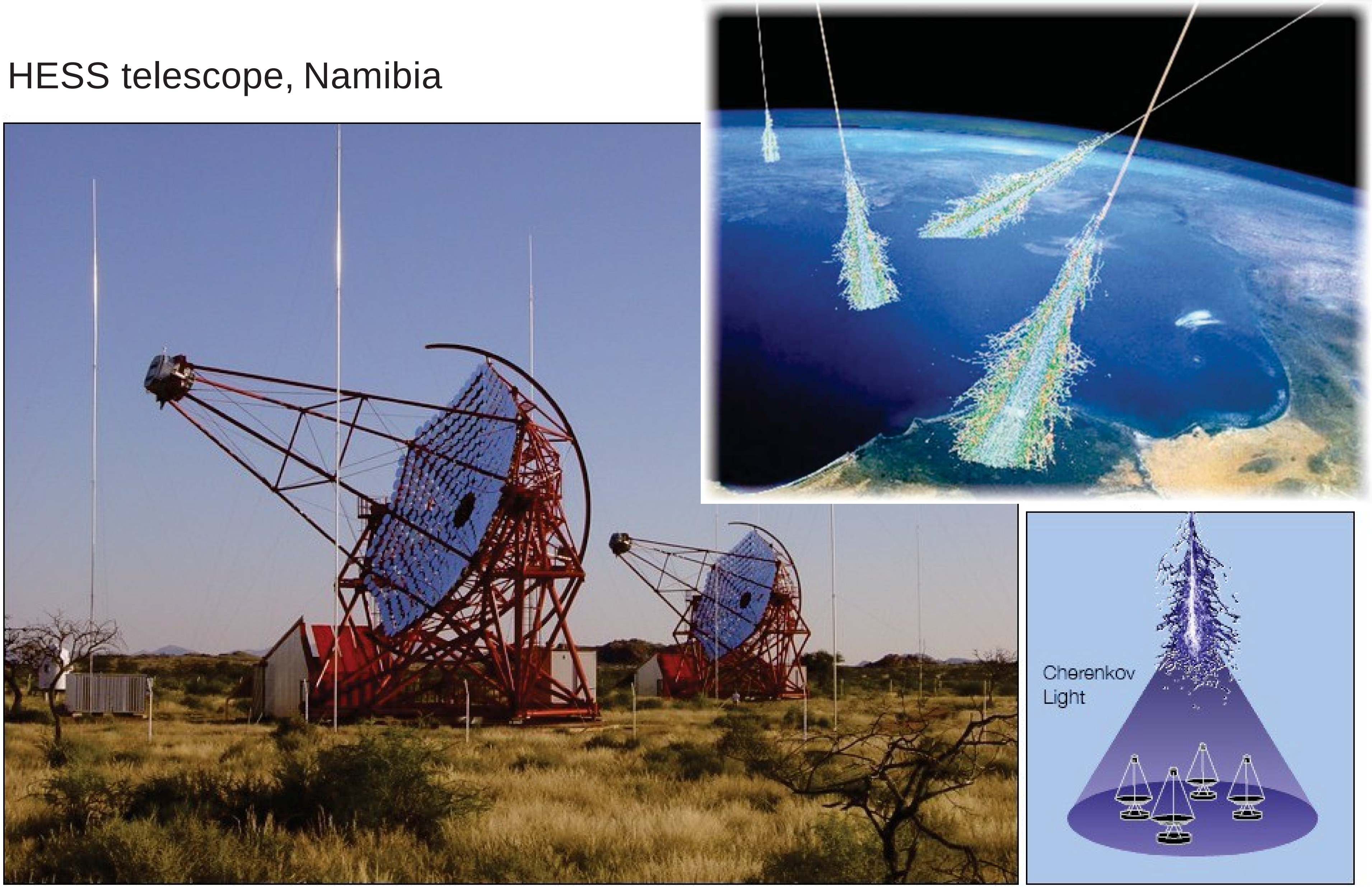


The Neutrino Cosmic-Ray Connection



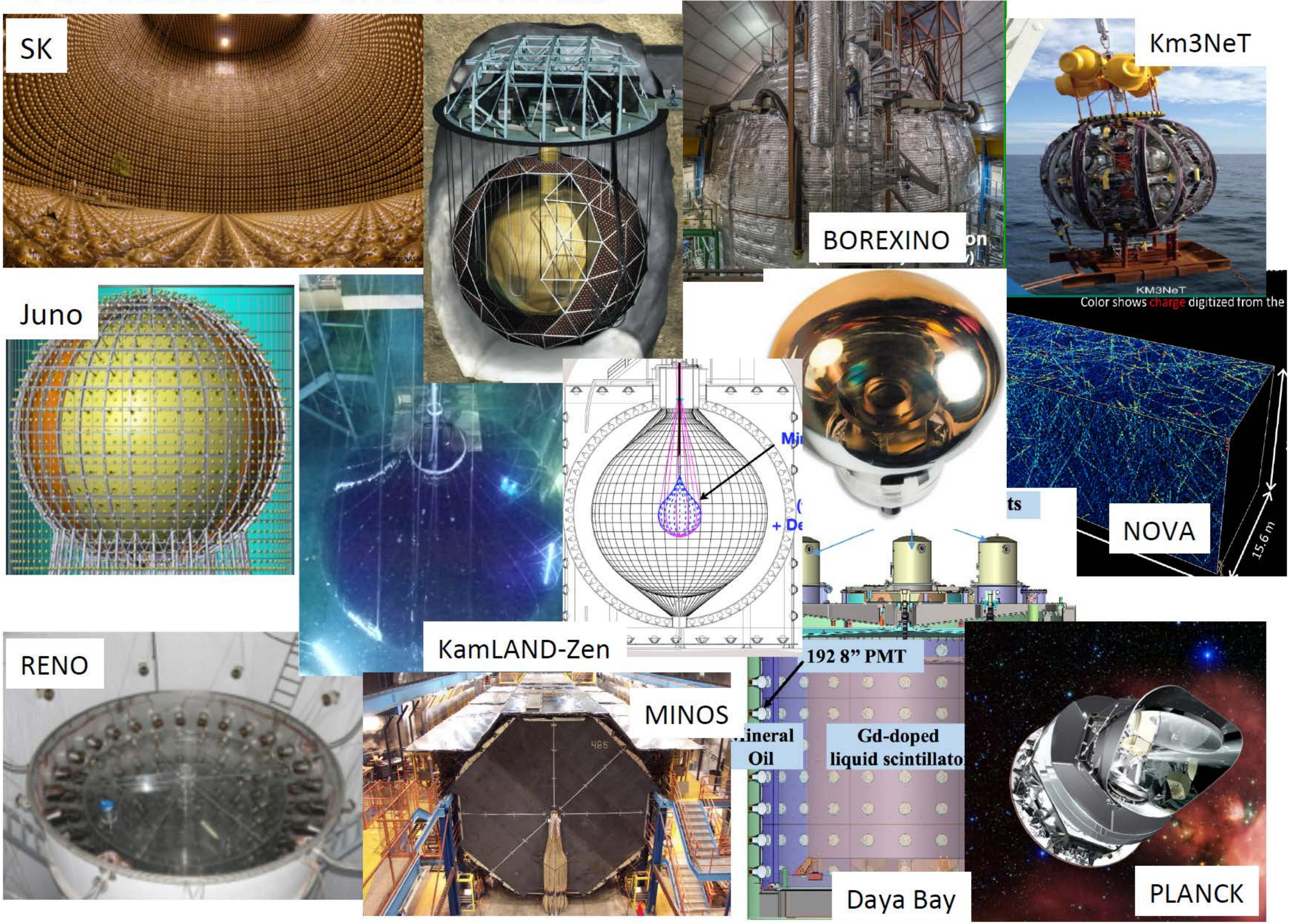
Particle detector: Cosmic rays detector

HESS telescope, Namibia



Our balloons… and vessels…

For Neutrino detection : calorimetry



A many facets problematic: sources

The neutrino detection techniques encompasses several different methodology of widespread use in the general field of particles detection.

The multiplicity of the detection methods is enhanced by the plurality of experimental needs posed by the different neutrino sources of experimental interest:

- solar neutrinos
- atmospheric neutrinos
- reactor neutrinos **and geo-neutrinos (anti-ν)**
- accelerator neutrinos
- supernova neutrinos
- ultra high energy neutrinos from astrophysical sources

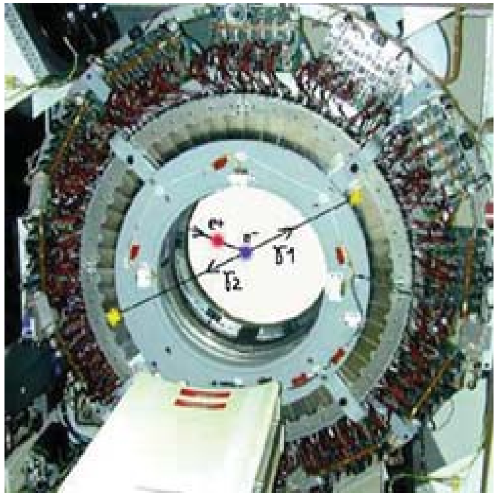
Neutrino detection

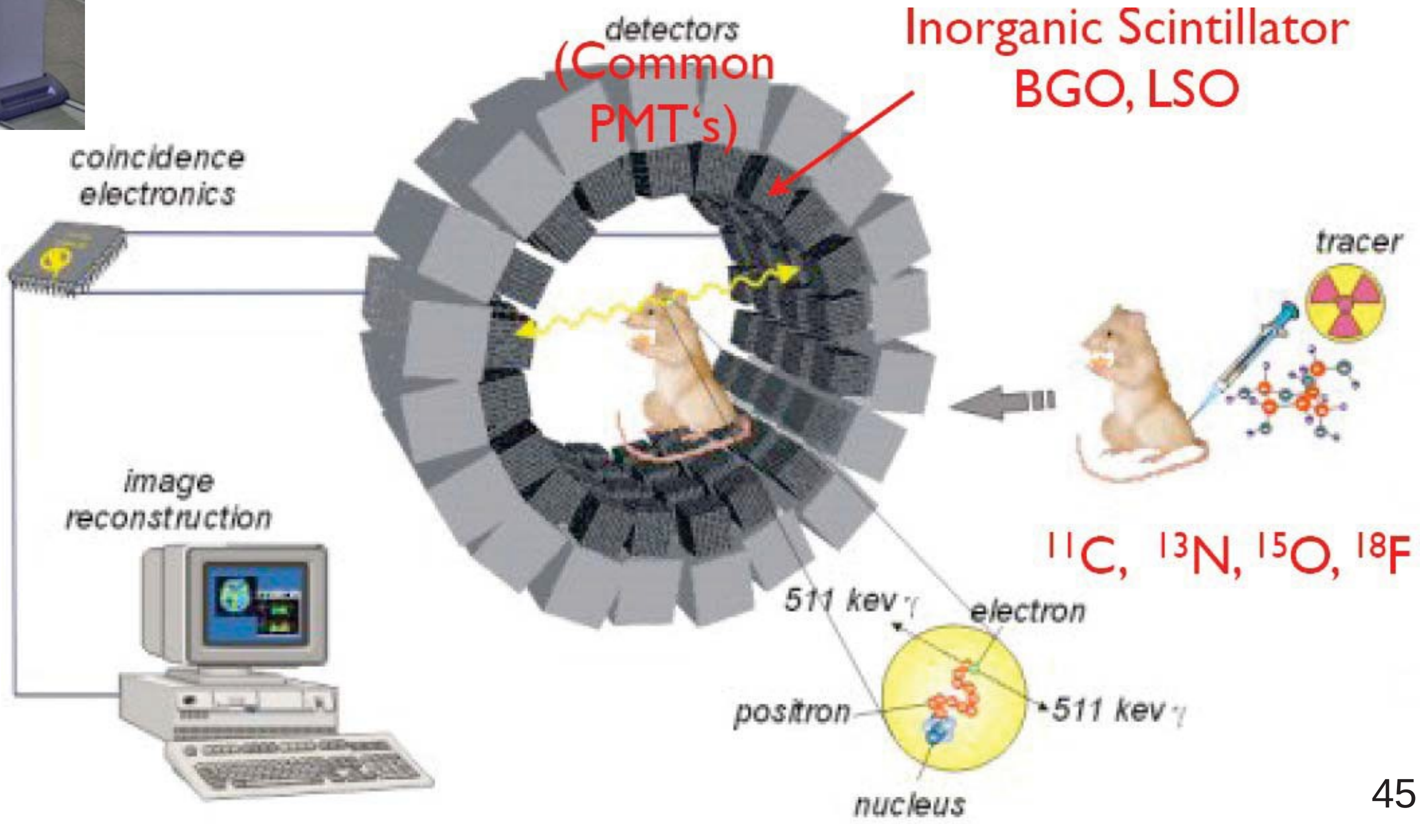
A many facets problematic: experimental methods

The richness of the neutrino physics field finds almost naturally its counterpart in the variety of techniques applied or proposed by the experimentalists to cover this broad range of applications:

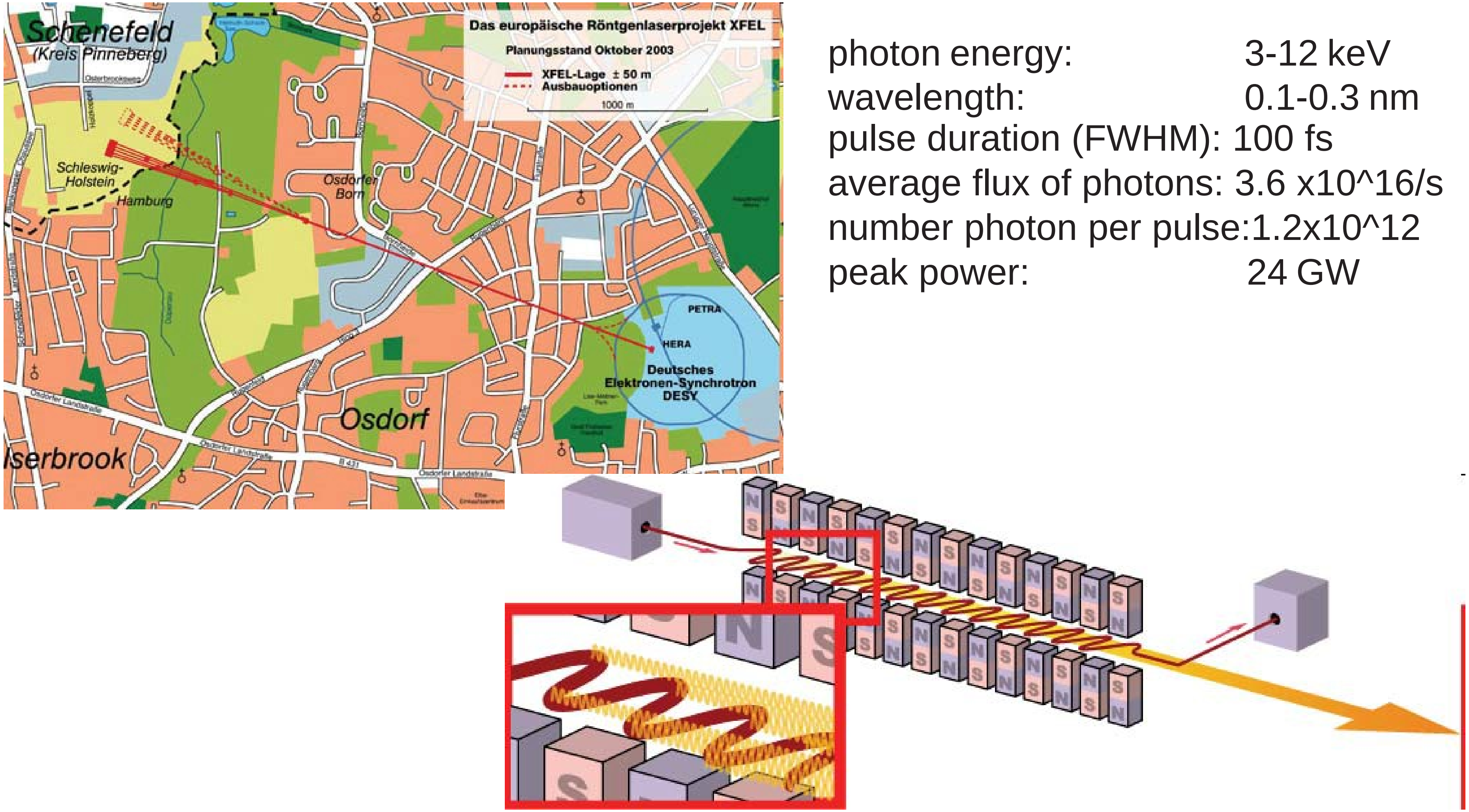
- Radiochemical methods
- Water cerenkov detectors
- Heavy water detectors
- Scintillation techniques
- Long string, large Water Cerenkov Detectors
- Time projection chambers
- Nuclear emulsions

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 x10^16/s
number photon per pulse:	1.2x10^12
peak power:	24 GW

Summary

- More than 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)
- Todays 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