Introduction: The Physics of Particle Detectors

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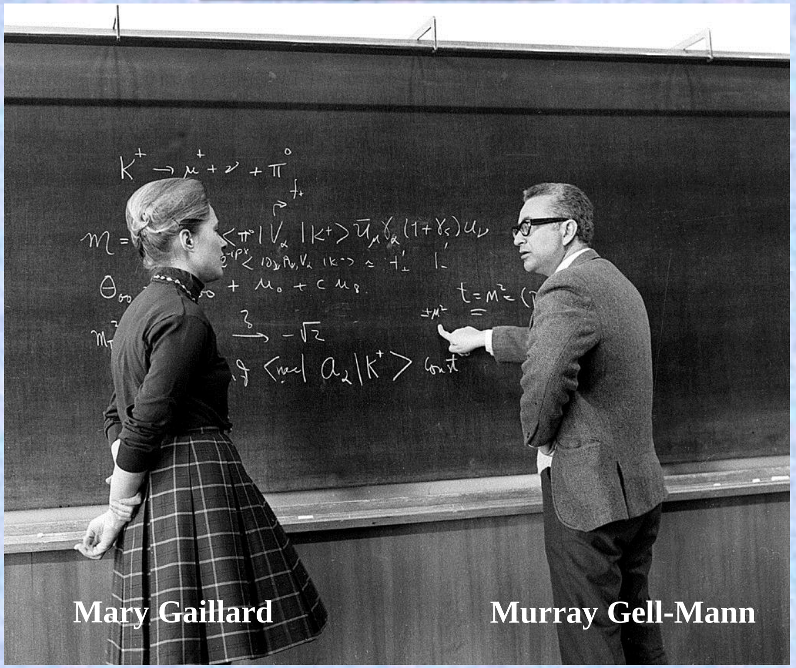
OUTLINE OF THE LECTURE:

➢ **We are presented with so many measurements (cross section, limits, …) that we often forget that we are talking about instruments and the measurements they have made, and the methods have been used.**

➢ **The surprise is how precise the detectors themselves are; the challenge of the modern experiments is to exploit that precision in the regime where statistics might be no longer a problem, and everything is dominated by the performance of the detector ('systematics').**

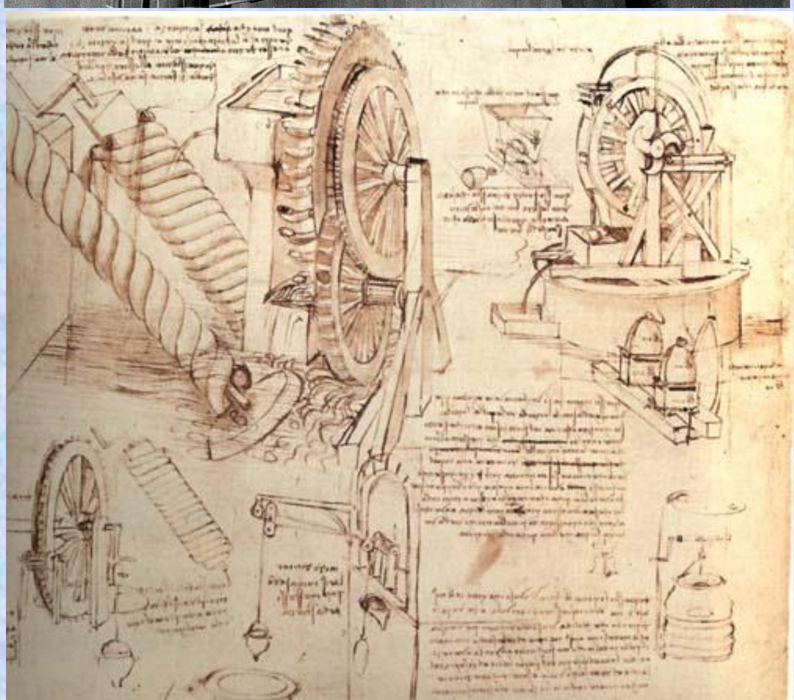
Ukrainian and Estonian Teachers Program 2012,
CERN, October 14-20, 2012

To do a HEP experiment, one needs:

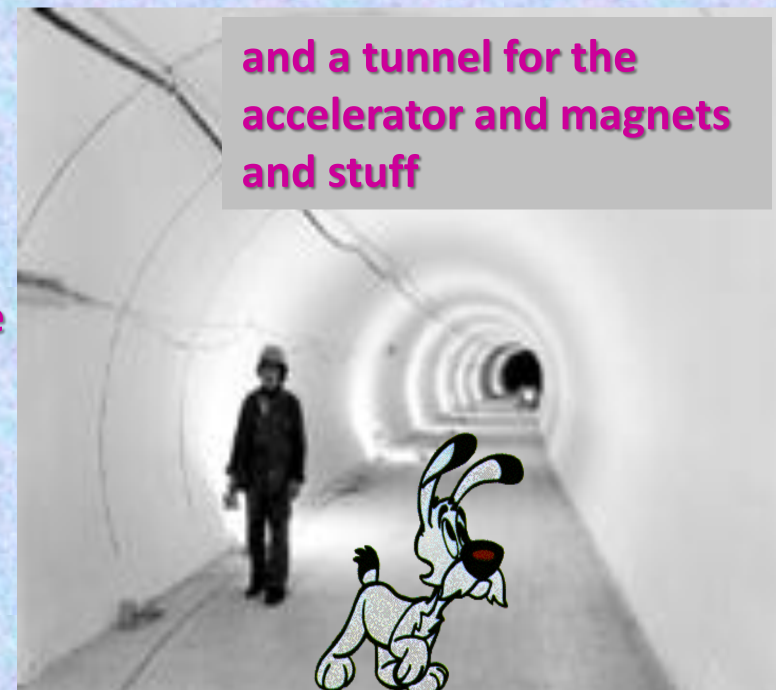


A theory:

and a cafeteria



Clear and easy understandable drawings

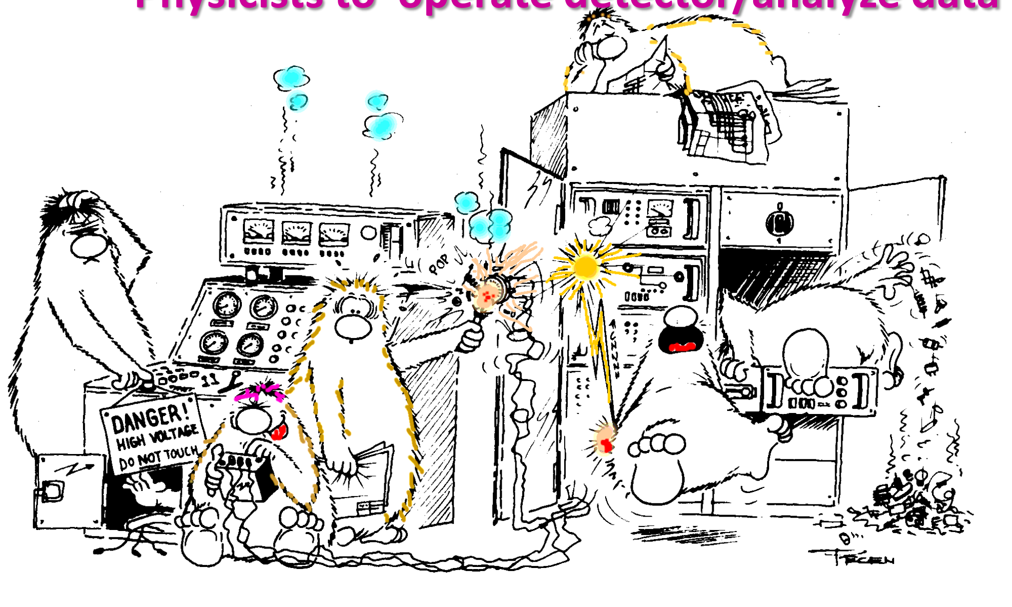


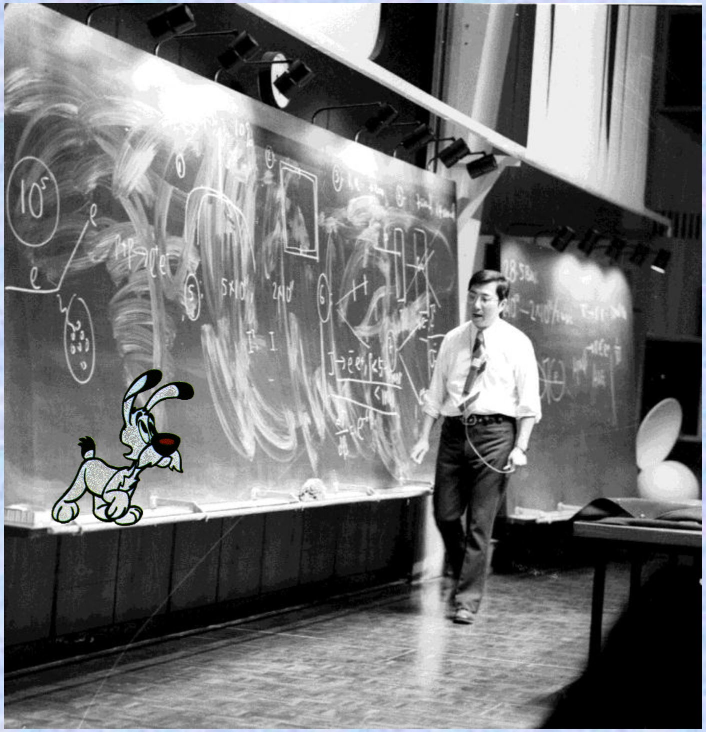
and a tunnel for the accelerator and magnets and stuff

O. Ullaland/2006

Easy access to the experiment

Physicists to operate detector/analyze data



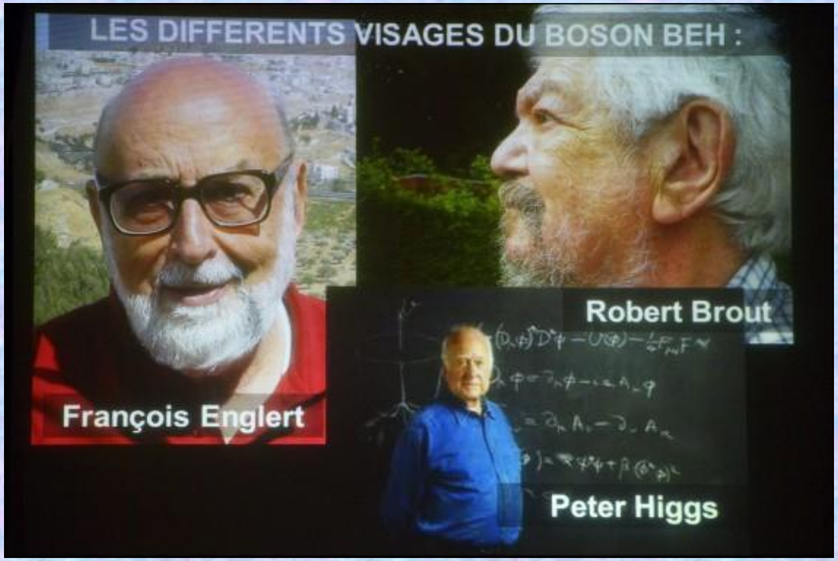


and a Nobel prize

We will just concentrate on the detectors

O. Ullaland/2006

“So, We have it – It is a Discovery”
(R. Heuer, CERN Director General, 4/7/2012)



Geneva, July 4, 2012:
Both ATLAS and CMS Collaborations have reported observation of a narrow resonance ~ 125 GeV consistent with long-sought Higgs boson

What do we know now: **it is a scalar particle (first scalar particle we ever observed) – and most probably “A HIGGS BOSON” - we need to establish if it is “THE HIGGS BOSON” of a Standard Model or not**

Evolution of Detector Concepts in HEP (I)

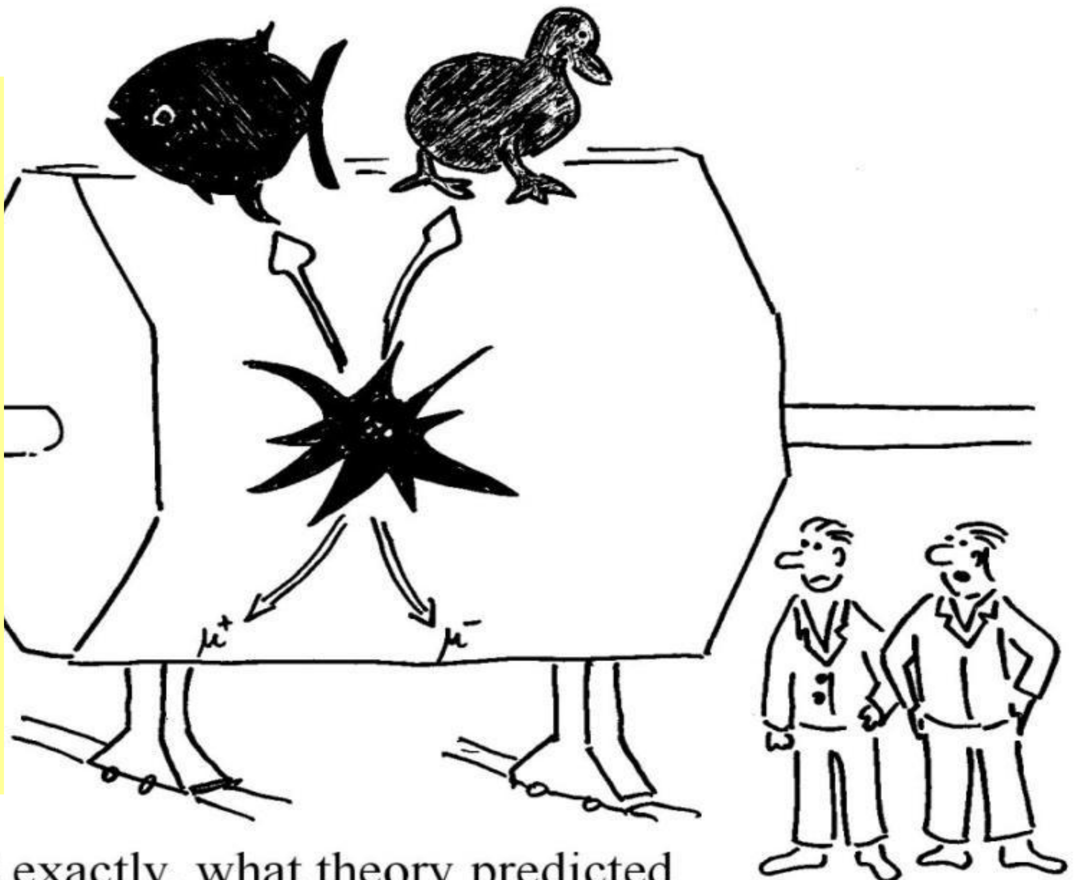
is always driven by the physics requirements and the experimental conditions

- **SM Particle Physics is more than hunting for Higgs…**

Need to make very <u>advanced systems</u>

Forefront of:

- ➢ **Accelerator Technology**
- ➢ **Detector Technology:**
  - → **Engineering**
  - → **Imaging Sensors**
  - → **Electronics**
  - → **Computing (web, GRID)**



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

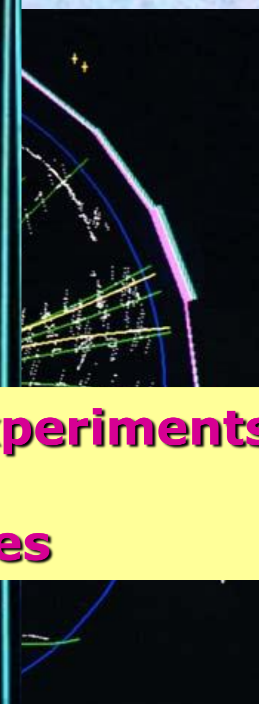
- **NATURE WILL, IN ALL LIKELIHOOD, SURPRISE US !**

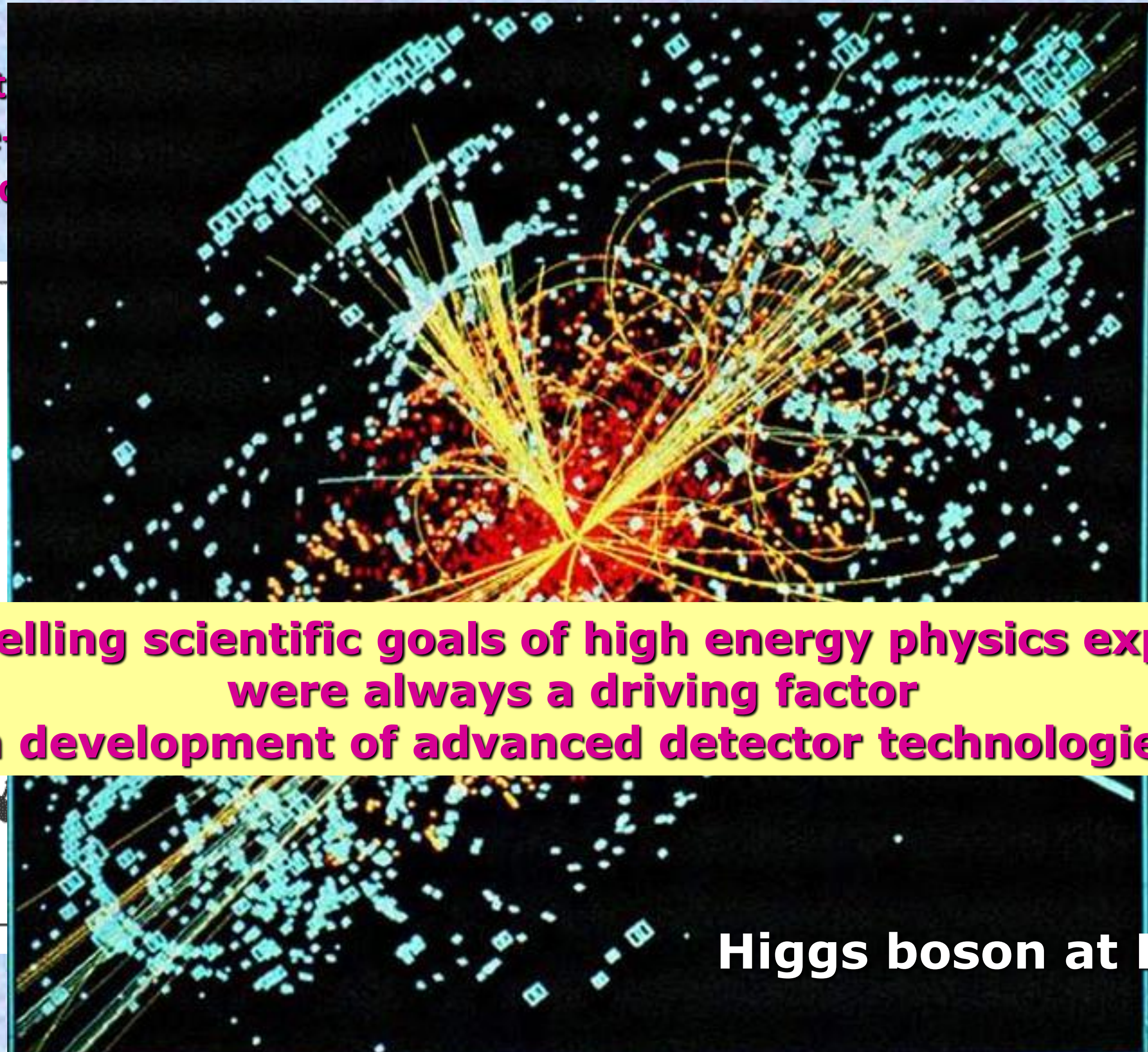
Evolution of New Detector Concepts in HEP (II)

INCREASING CHALLENGES ...

MARK-I det
e+e-
Ψ´ (exc

y at CDF
,8 TeV)





Higgs boson at LHC

The compelling scientific goals of high energy physics experiments were always a driving factor in development of advanced detector technologies

History of Instrumentation (I)

Image Detectors

Bubble chamber photograph

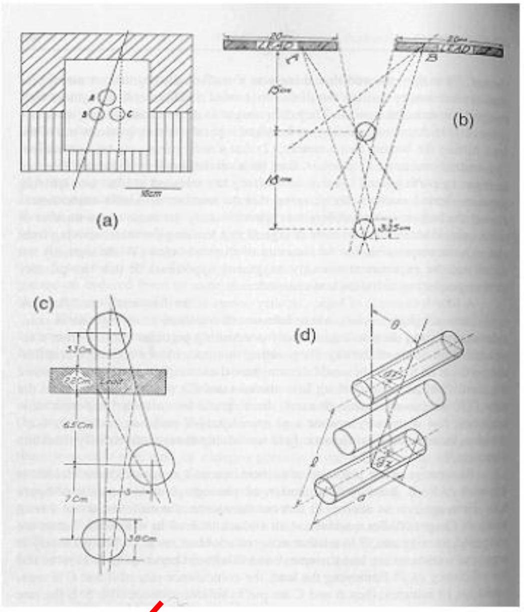
History of 'Particle Detection'

Image Tradition: Cloud Chamber
Emulsion
Bubble Chamber

Logic Tradition: Scintillator
Geiger Counter
Tip Counter
Spark Counter

Electronics Image: Wire Chambers
Silicon Detectors
…

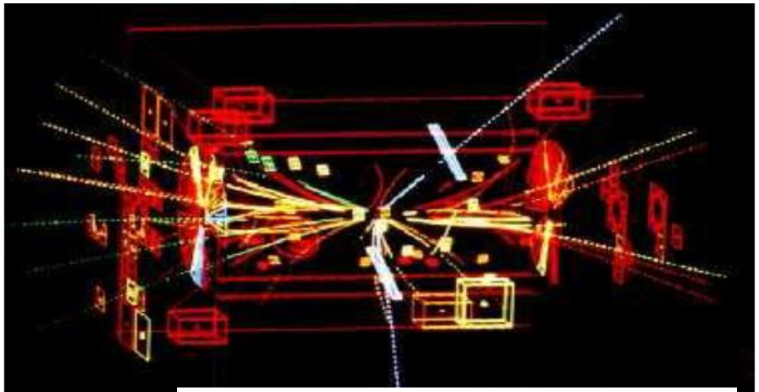
'Logic (electronics) Detectors'



Early coincidence counting experiment

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
Etc. etc. etc.

Both traditions combine into the 'Electronics Image' during the 1970ies



Z-Discovery at UA1 CERN in 1983

History of Instrumentation (II)

A look at the history of instrumentation in particle physics gives a complementary view on the history of particle physics, which is traditionally told from a theoretical point of view.

This history of instrumentation is in addition quite entertaining. The importance and recognition of inventions is the field of instrumentations is proven by the fact that several Nobel Prices in physics were awarded mainly or exclusively for the development of detection techniques.

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

1939: E. O. Lawrence, Cyclotron & Discoveries

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

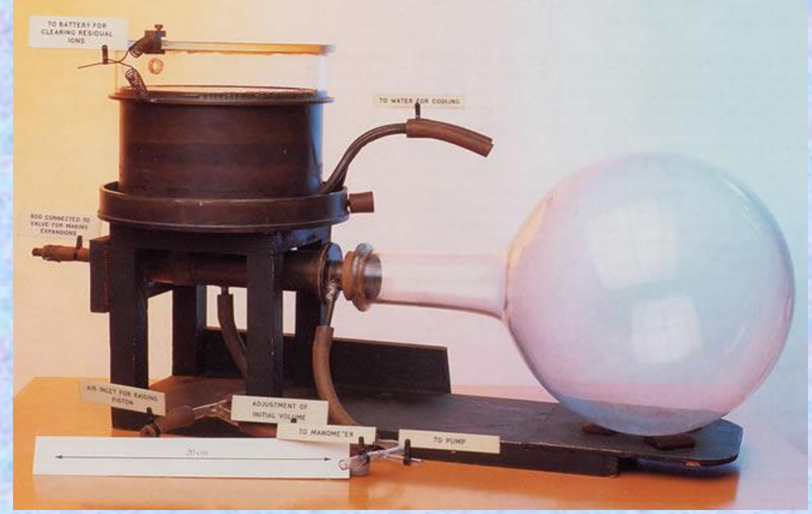
1950: C. Powell, Photographic Method & Discoveries

1954: Walter Bothe, Coincidence Method & Discoveries

1960: Donald Glaser, Bubble Chamber

1968: Luis Alvarez, Bubble Chamber & Discoveries

1992: Georges Charpak, Multi Wire Proportional Chamber



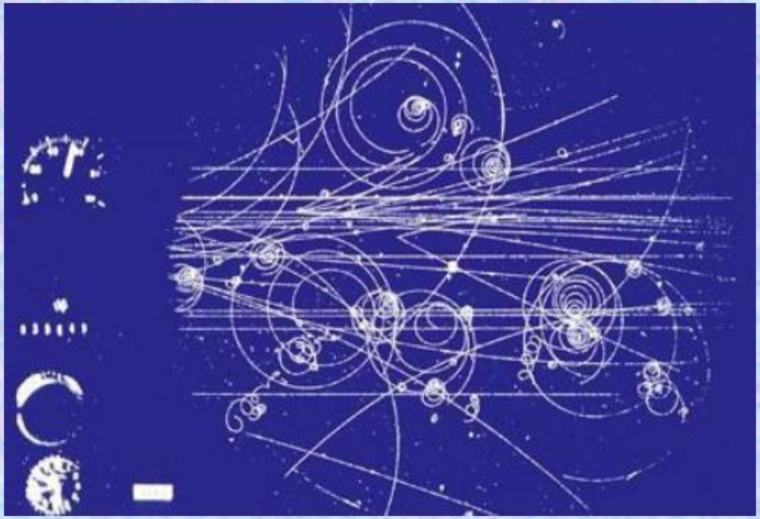
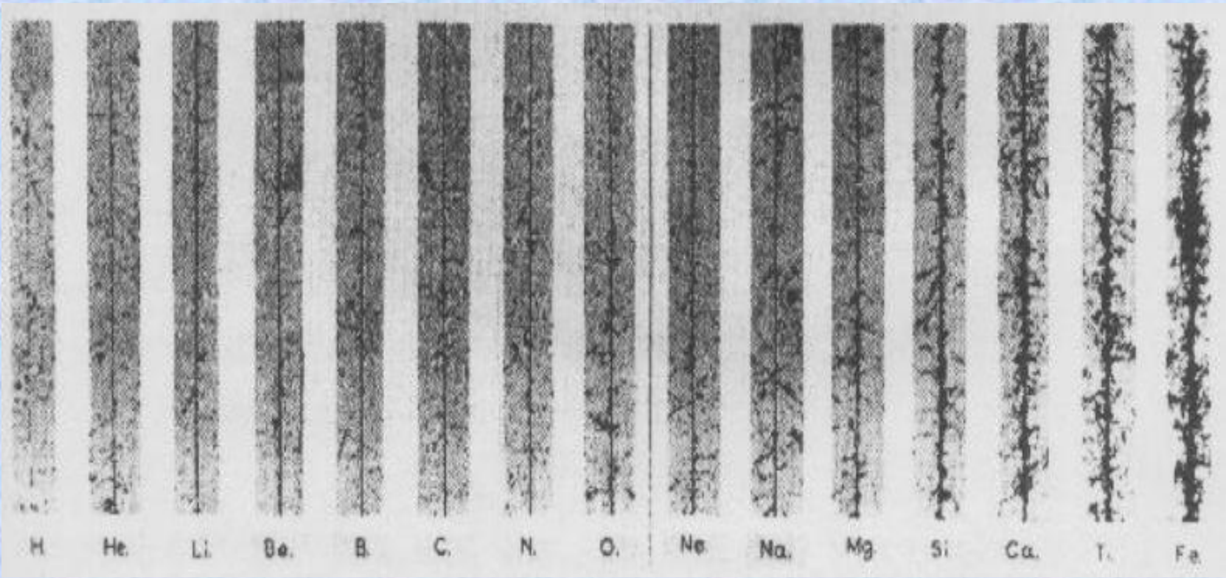
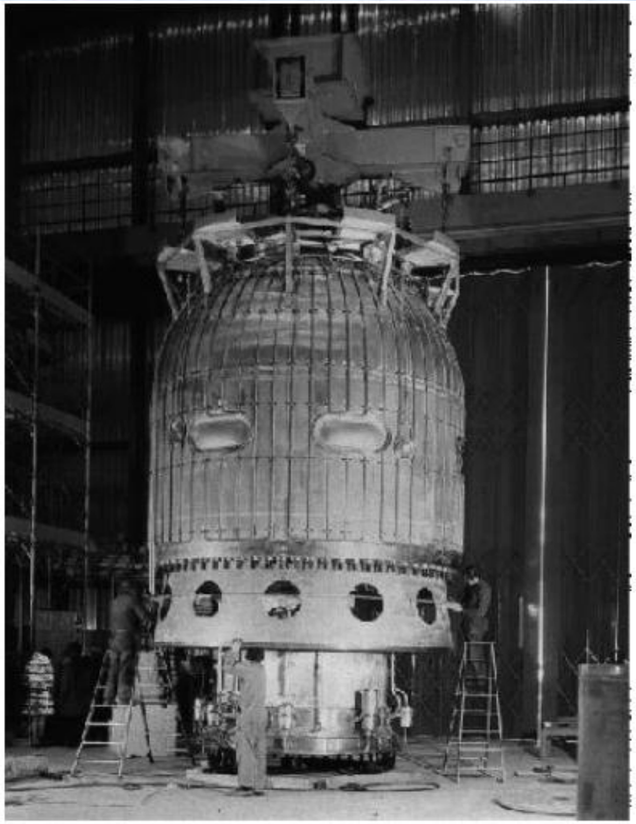


Image Detectors
(Cloud Chamber, Emulsion, Bubble Chamber)

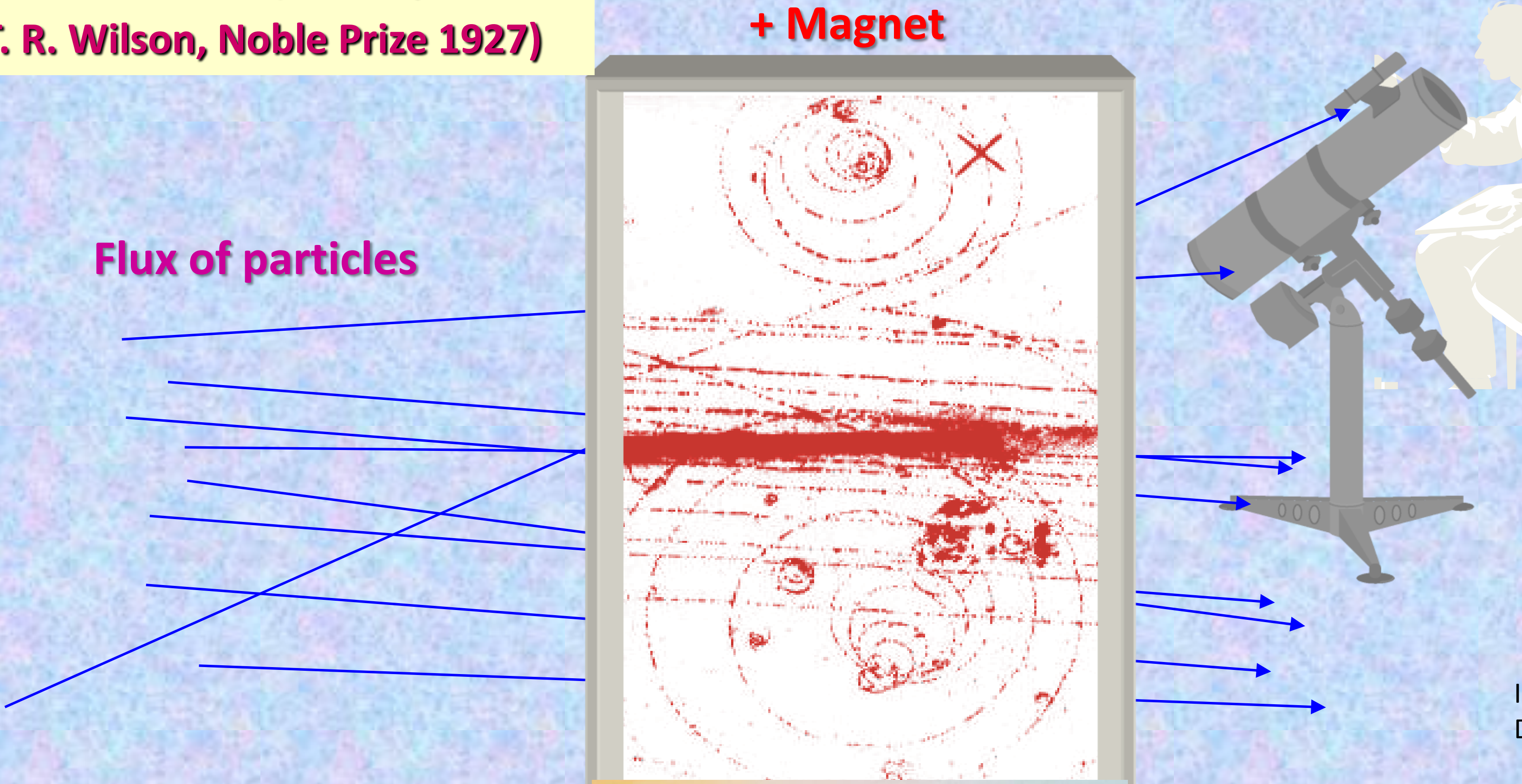




Can be seen outside the Microcosm Exhibition

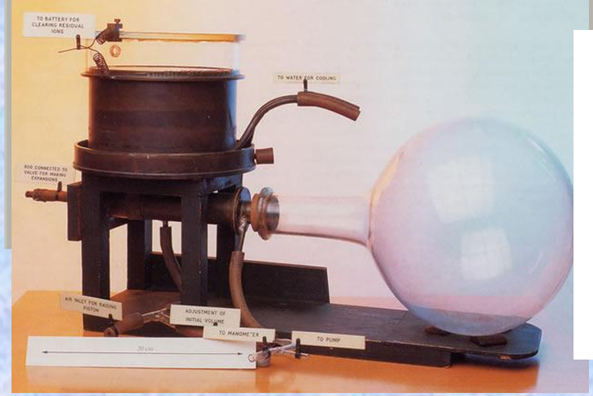
First Tracking Detector: Wilson Chamber

Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)



INDIVIDUAL DOSIMETER

Allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure → over-saturated volume of air



Passage of charge particle would condense the vapor into tiny droplets, marking the particle's path → their number being proportional to dE/dx

O. Ullaland/2006

Discovery of a Positron e+ from Cosmic Rays

1932 C.D. Anderson :
Particle with positive curvature and minimum ionisation (size of the droplets)

Track length incompatible with a proton in the air, mass incompatible with a proton

Energy loss in a 6 mm of Pb : compatible with that of electron

<u>Hypothesis (discovery !) :</u>
particle with mass ~m_e and charge +1, the positron

First anti-particle

CARL D. ANDERSON

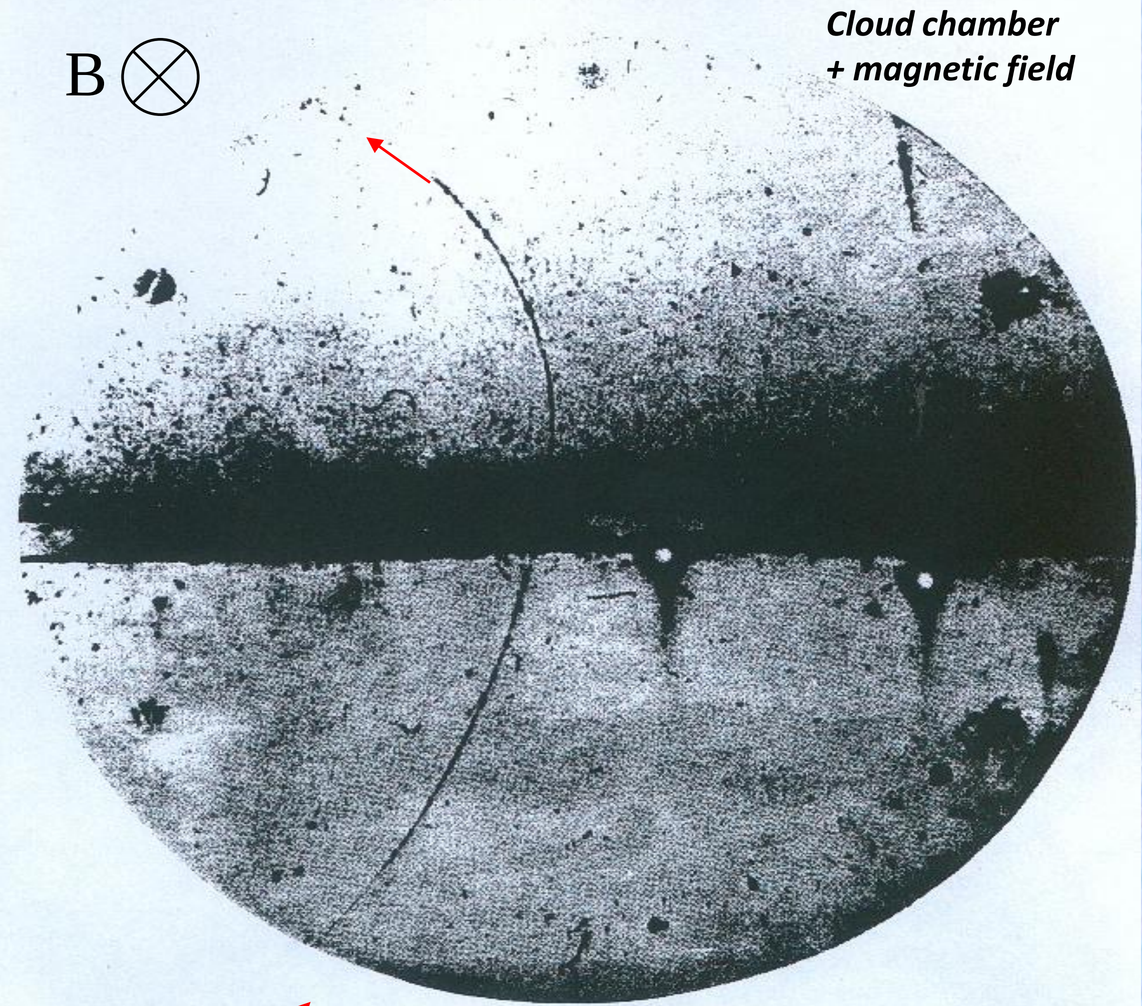
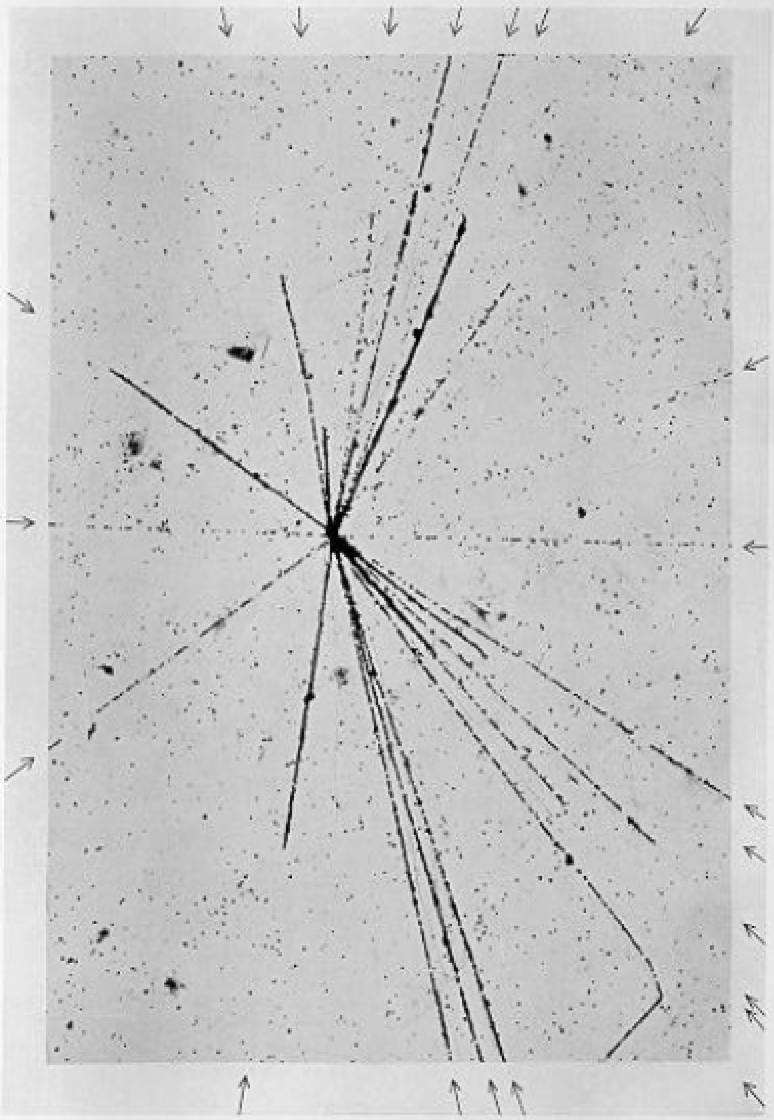


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plat and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Cloud chamber was used for a discovery of the positron (1932 by Carl Anderson, Noble Prize 1936)

Nuclear Emulsion



'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

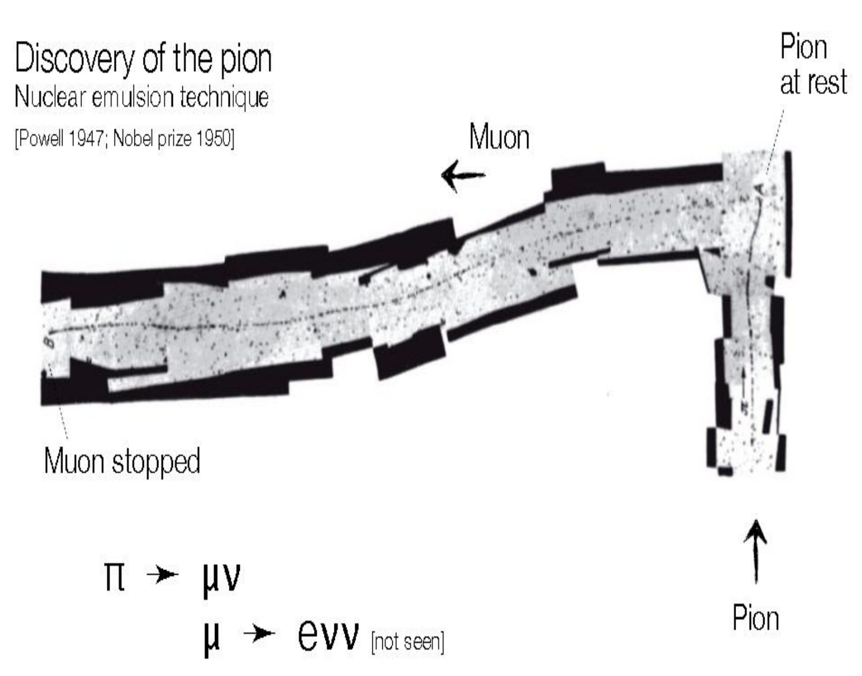
Film played an important role in the discovery of radioactivity but was first seen as a means of studying radioactivity rather than photographing individual particles.

Between 1923 and 1938 Marietta Blau pioneered the nuclear emulsion technique.

E.g.
Emulsions were exposed to cosmic rays at high altitude for a long time (months) and then analyzed under the microscope.
In 1937, nuclear disintegrations from cosmic rays were observed in emulsions.

The high density of film compared to the cloud chamber 'gas' made it easier to see energy loss and disintegrations.

Nuclear Emulsion: Discovery of the Pion



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.

A result analog to the cloud chamber can be obtained with a picture 1000x smaller (emulsion density is about 1000x larger than gas at 1 atm).

Due to the larger 'stopping power' of the emulsion, particle decays could be observed easier.

Stacks of emulsion were called 'emulsion chamber'.

(1947 by Powell, Noble Prize 1950)

Bubble Chamber

Donald Glaser

LBNL Image Library

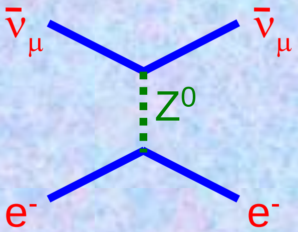
Similar principle as cloud chamber:

Bubble chamber (1952 by Donald Glaser, Noble Prize 1960)

– (4.8 x 1.85 m^2) chamber with liquid (e.g. H_2) at boiling point ("superheated")

- **Instead of supersaturating a gas with a vapor one would superheart the liquid.**

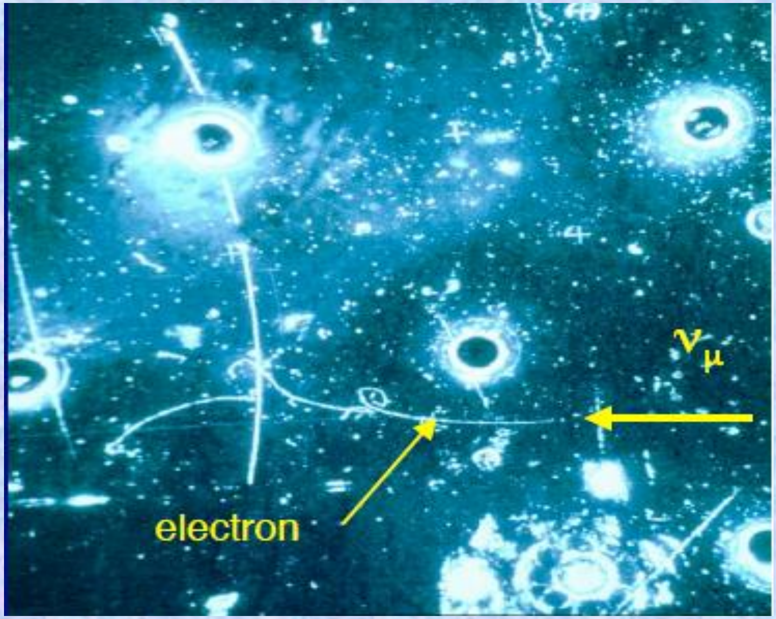
- **A particle leave a trail of ions along its path → make a liquid boil, and form gas bubbles around ions**



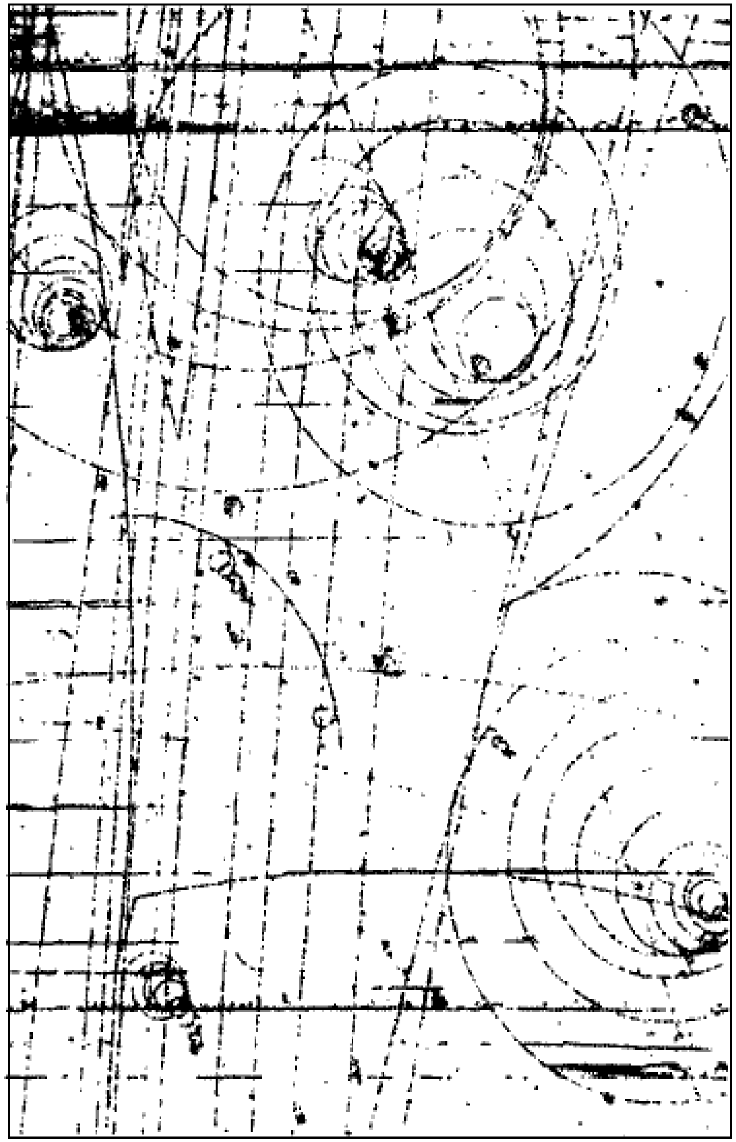
was used at discovery of the "neutral current" (1973 by Gargamelle Collaboration, no Noble Prize)

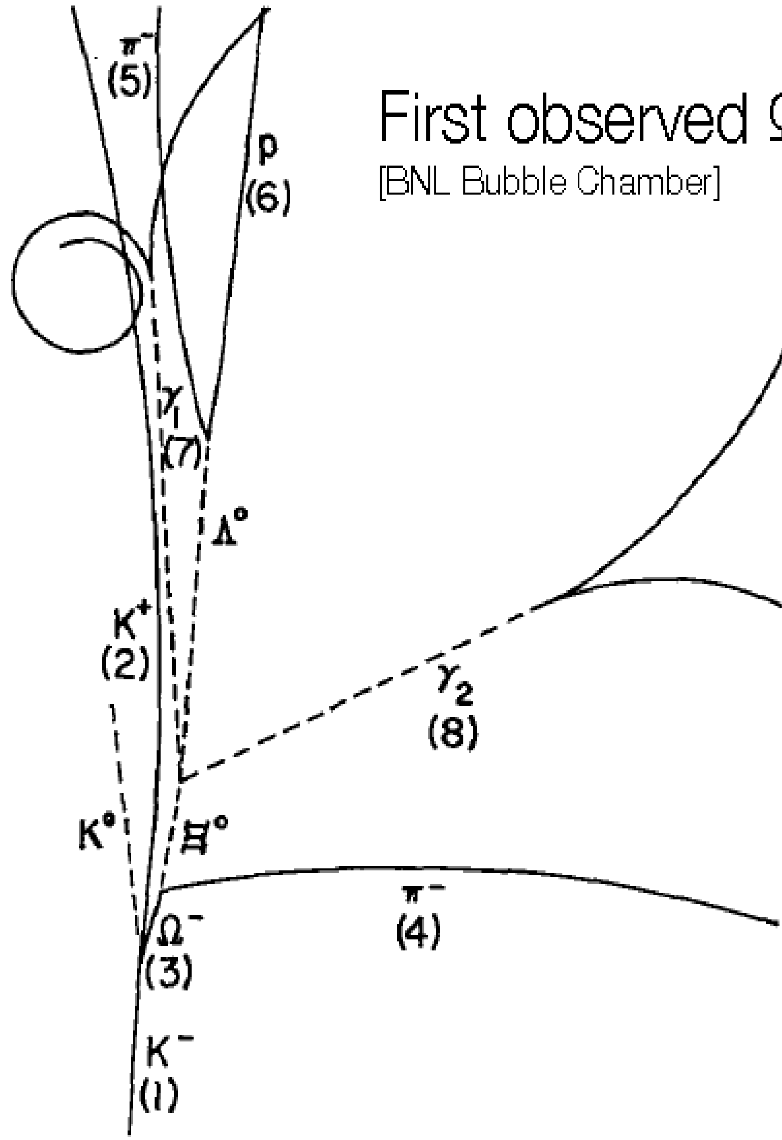
Gargamelle bubble chamber

CERN



Bubble Chamber





First observed Ω^- event

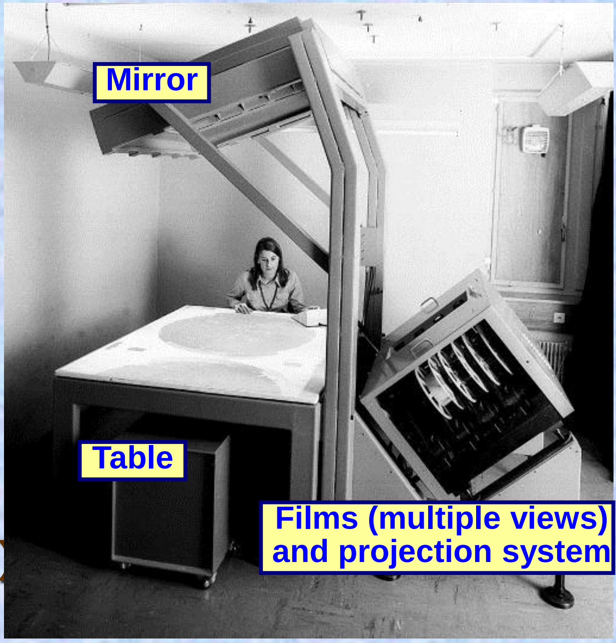
[BNL Bubble Chamber]

"Classic" Particle Detectors - Bubble Chambers

- **Advantages of bubble chambers**
  - **liquid is**

    BOTH detector medium

    AND target
  - **high precision**



Scanning table (1972)

- **Disadvantages**

  - NO TRIGGER -> has to be in superheated state when particle is entering (unlike "Cloud chamber")

  - SLOW, Need FASTER detector (electronics !)

  - For data analysis one has to take HUGE NUMBER of PICTURES with cameras on film:
    - **film needs to be developed, shipped to institutes**
    - **and optically scanned for interesting events**

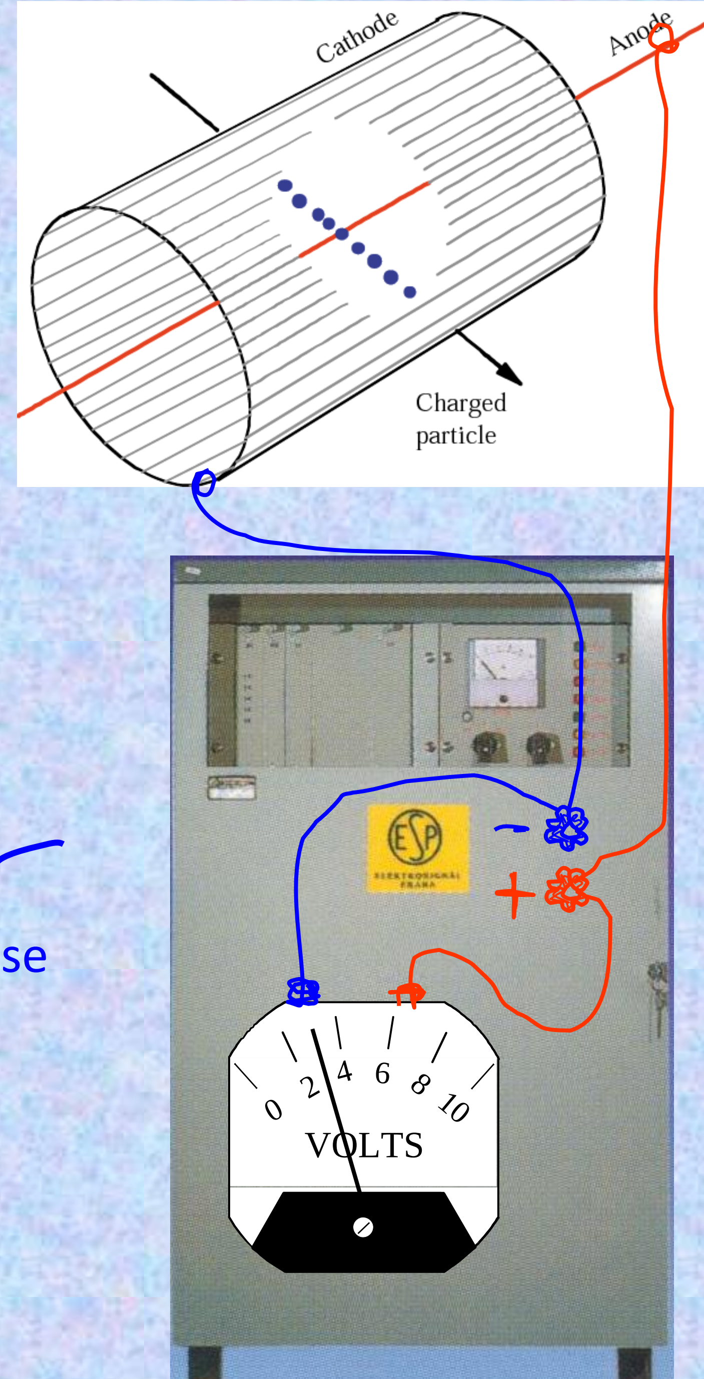
Important social aspects of bubble chamber era

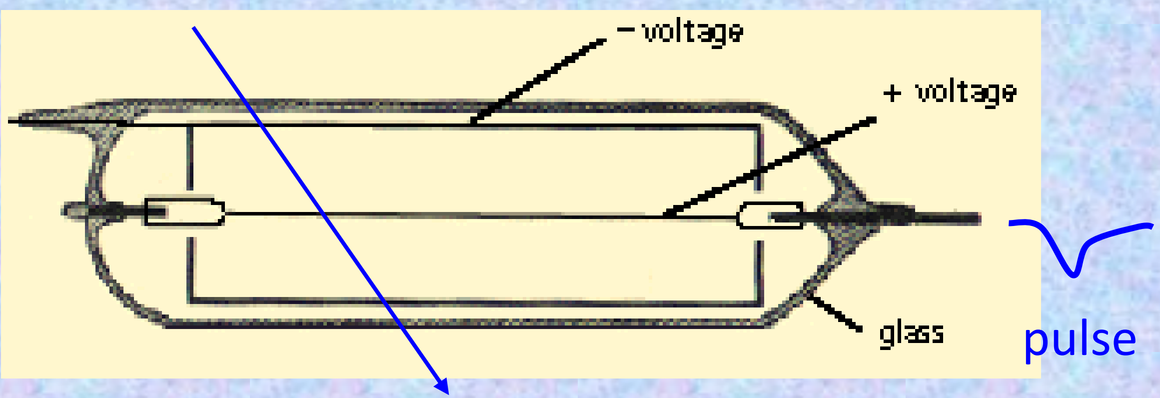
scanning often done by young "scanning girls" (students)...
...who later got married with the physicists...

Logic Detectors
(Geiger Counter, Scintillator, Spark Counter, MWPC, Silicon Detectors)

Geiger Counter

E. Rutherford 1909 H. Geiger 1927





The Geiger counter, later further developed and then called Geiger-Müller counter

First electrical signal from a particle

E. Rutherford and H. Geiiger, Proc. Royall Soc. A81 (1908) 141

H. Geiiger and W. Müllller, Phys. Zeits. 29 (1928) 839

Neher 1938, Procedures in Experimental Physics

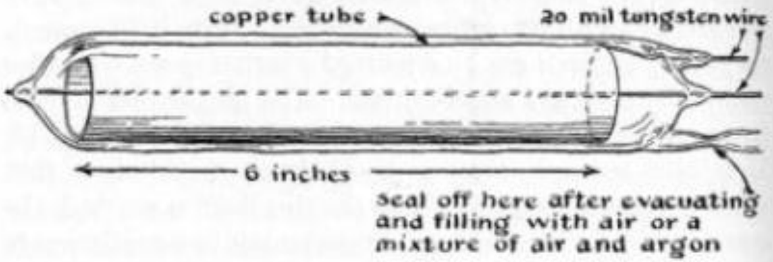


Fig. 9. Typical construction of a copper-in-glass counter. Following this general design, counters have been made from 0.5 cm to 10 cm in diameter.

Although both positive and negative particles are present in the tube, the actual multiplying agents are probably the electrons. The electric field is higher than necessary for the electrons to form ions by collision, while it is probably not high enough for the positive or negative ions to do so. The electrons rushing toward the wire form new positive ions and electrons, the current building up according to the law $i = i_0e^{\alpha x}$, where α is the number of new pairs of ions formed per centimeter of path and is called the Townsend coefficient. Probably negative ions are also formed by the attachment of electrons to the molecules. In the ionization process light is given off, liberating new electrons from the metal tube, and these, in turn, form other ions as they rush toward the wire. This photoelectric process has been found by Christoph and Hanle[6] and by Locher[7] to be important in the mechanism of the discharge. The process of accumulative ionization continues until the potential difference between the cylinder and the wire has dropped to a point where ionization by collision can no longer occur. The po-

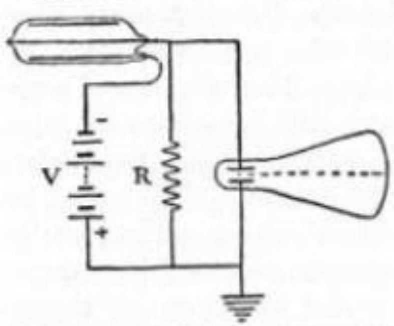


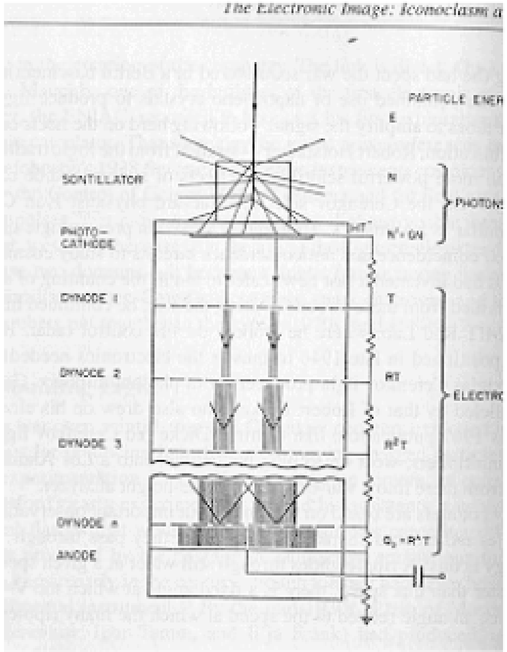
Fig. 6. The action of a counter is best studied with a cathode-ray oscillograph.

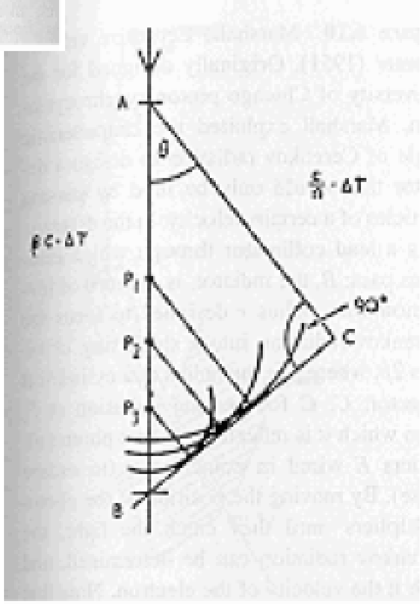
The procedure to make a *fast* counter is as follows:

1. Starting with a copper-in-glass counter with a tungsten wire, clean the copper thoroughly with about 6 normal nitric acid. (A water aspirator is indispensable for admitting and removing solutions.) Such a concentration of acid will leave the copper very bright.
2. After rinsing well, introduce a solution of 0.1 normal nitric acid. This will remove any copper compounds formed by the stronger acid.
3. Rinse thoroughly (at least 10 times) with distilled water and dry.
4. With dry air inside, heat the whole counter in a large flame until the copper turns a uniform brownish-black color.
5. Seal the counter off temporarily and then heat for several hours at about 400°C. Upon cooling, the copper cylinder will be coated with the bright red oxide, Cu_2O.
6. Evacuate and admit dry NO_2 gas to a pressure of 1 atmosphere. (This gas can be made by the action of 16 normal nitric acid on copper. It may be dried by passing through $CaCl_2$ and P_2O_5.)
7. Heat the counter with the NO_2 until the Cu_2O turns a dark velvety color. Pump out the NO_2.
8. Admit argon (commercial, 99 per cent pure is satisfactory), which has been bubbled through xylene, to a pressure of 6 to 10 cm of mercury pressure. The counter should be tried at this point. For a 1-inch counter the threshold should be 600 to 800 volts for 8 cm of mercury pressure. If the counter does not work properly, the gas should be pumped out and more argon, which has been bubbled through the xylene, admitted.
9. When the counter is found to work satisfactorily, it may be sealed off.

Although all the above steps may not be necessary in all cases, yet this procedure has been found to give very satisfactory counters having reaction times of 10^{-5} second or better. The characteristics of the counters also seem to be permanent. The photoelectric properties as well as the electrical resistance of the surface are probably radically changed by this treatment.

Scintillators, Cherenkov Light, Photomultipliers





In the late 1940ies, scintillation counters and Cerenkov counters exploded into use.

Scintillation of materials on passage of particles was long known.

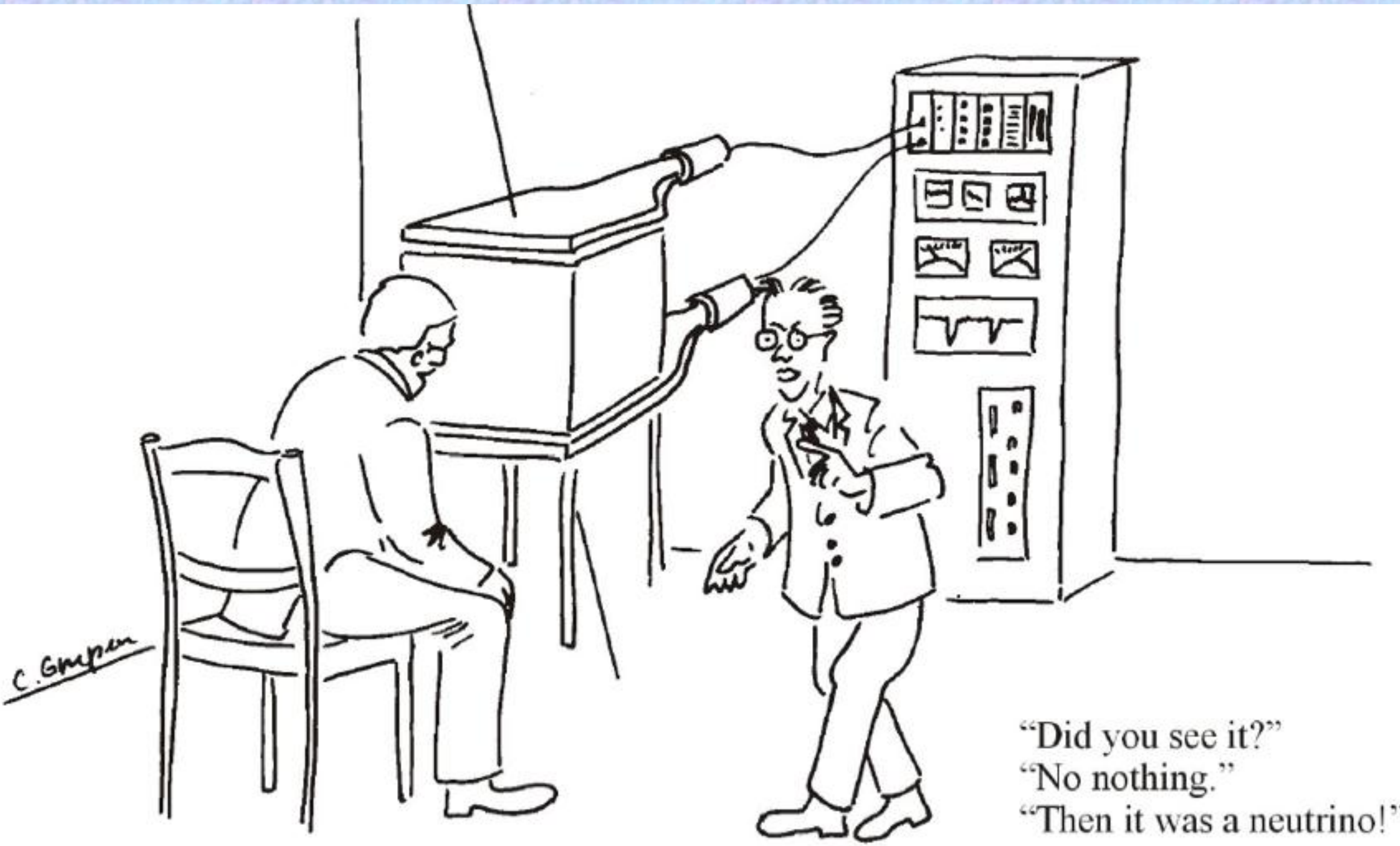
By mid 1930 the bluish glow that accompanied the passage of radioactive particles through liquids was analyzed and largely explained (Cerenkov Radiation).

Mainly the electronics revolution begun during the war initiated this development.

High-gain photomultiplier tubes, amplifiers, scalers, pulse-height analyzers.

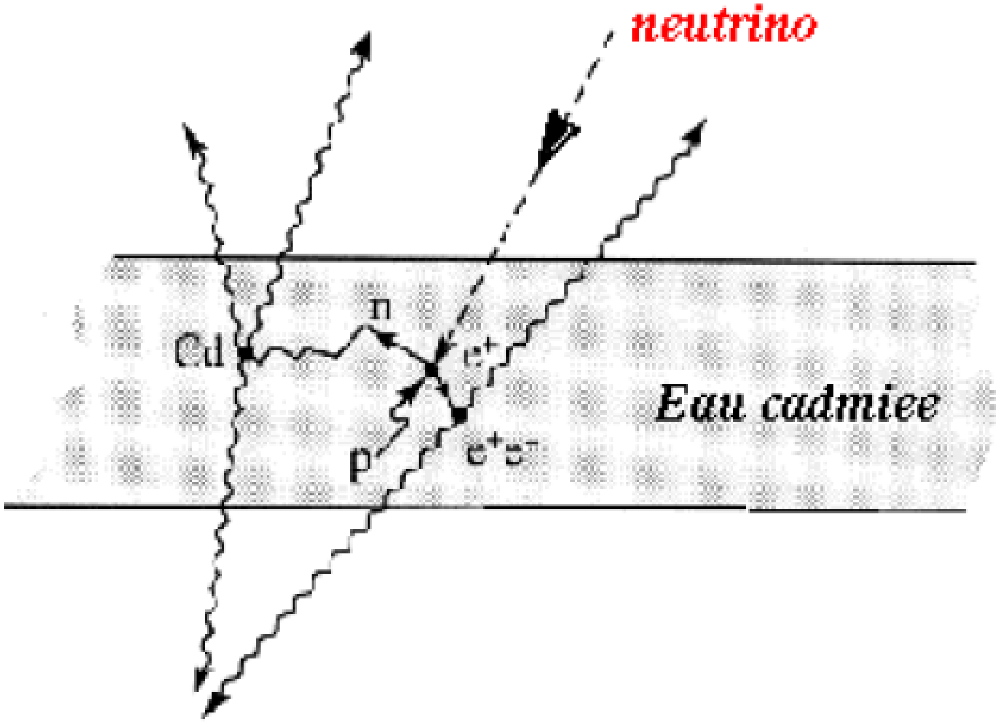
A Short Word on Neutrinos*

***… only true for experiments at accelerators**



Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

Anti-Neutrino Discovery (1959)



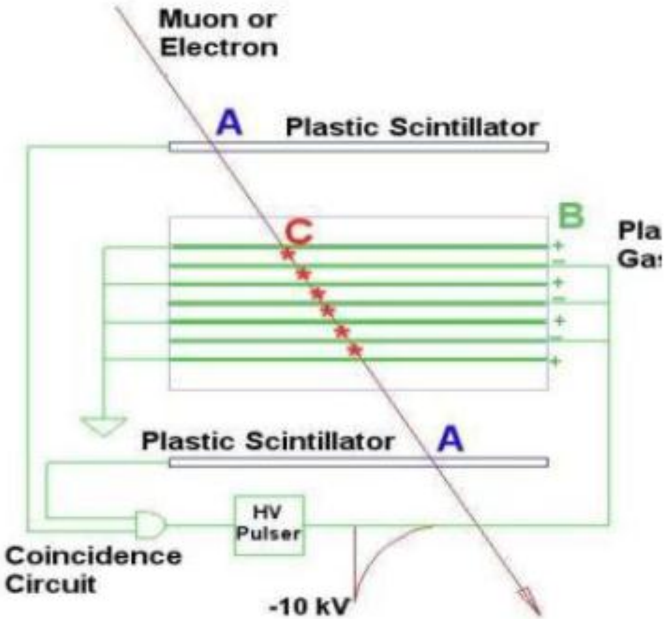
$\bar{\nu} + p \rightarrow n + e^+$

Reines and Cowan experiment principle consisted in using a target made of around 400 liters of a mixture of water and cadmium chloride.

The anti-neutrino coming from the nuclear reactor interacts with a proton of the target matter, giving a positron and a neutron.

The positron annihilates with an electron of the surrounding material, giving two simultaneous photons and the neutron slows down until it is eventually captured by a cadmium nucleus, implying the emission of photons some 15 microseconds after those of the positron annihilation.

Discovery of the Muon Neutrino (1962)



The Spark Chamber was developed in the early 60ies.

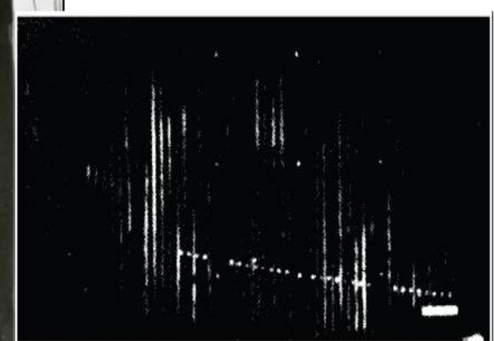
Schwartz, Steinberger and Lederman used it in discovery of the muon neutrino

The experiment used a beam of the energetic protons to produce a shower of π-mesons, which traveled toward a 5,000-ton steel wall made of old battleship plates. On the way, they decayed into muons and neutrinos, but only the latter particles could pass through the wall into a neon-filled detector called a spark chamber. There, the impact of neutrinos on aluminum plates produced muon spark trails that could be detected and photographed -- proving the existence of muon-neutrinos.

Discovery of the muon neutrino (1962)

(1962 by Lederman, Schwartz, Stainberger; Noble Prize 1988)

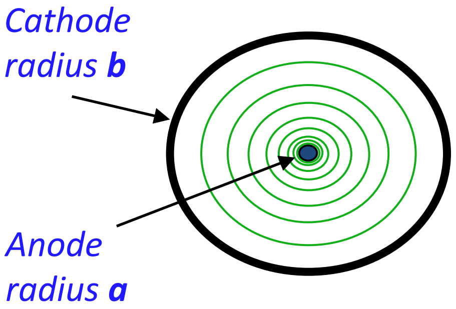
Melvin Schwartz in front of the spark chamber used to discover the muon neutrino



Single muon event from original publication

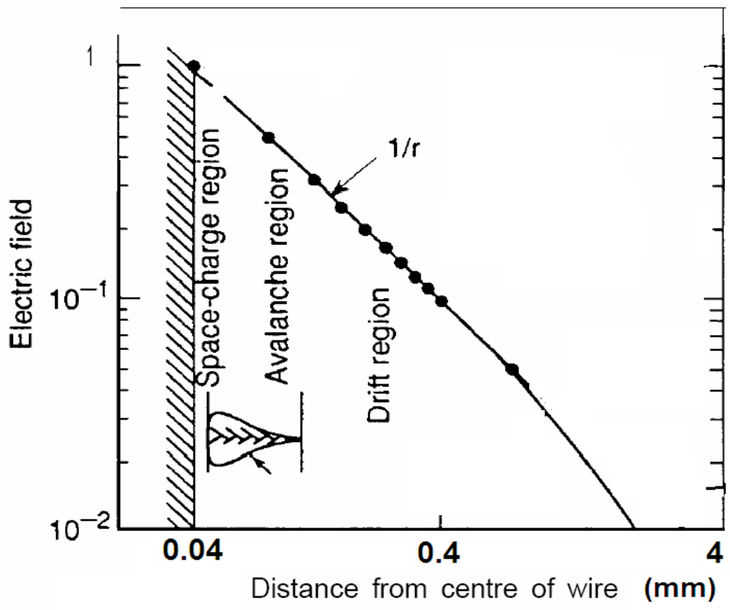
Single Wire Proportional Counter

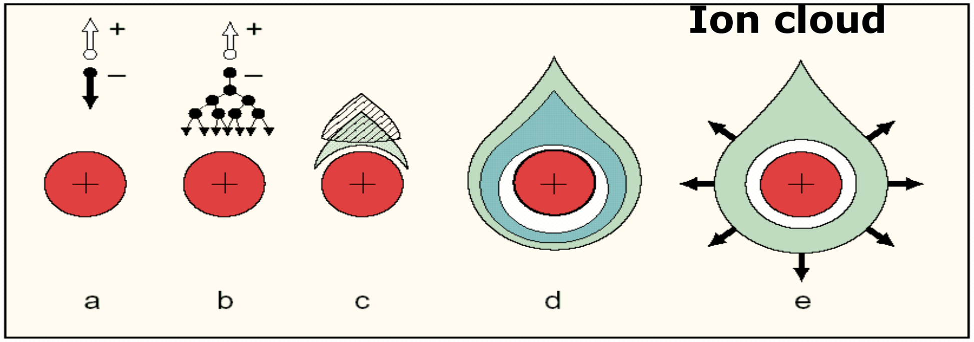
Thin anode wire (~20–50μm) coaxial with cathode:



$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

Avalanche development in the high electric field (~ 250 kV/cm) around a thin wire (multiplication region ~ 100 μm):



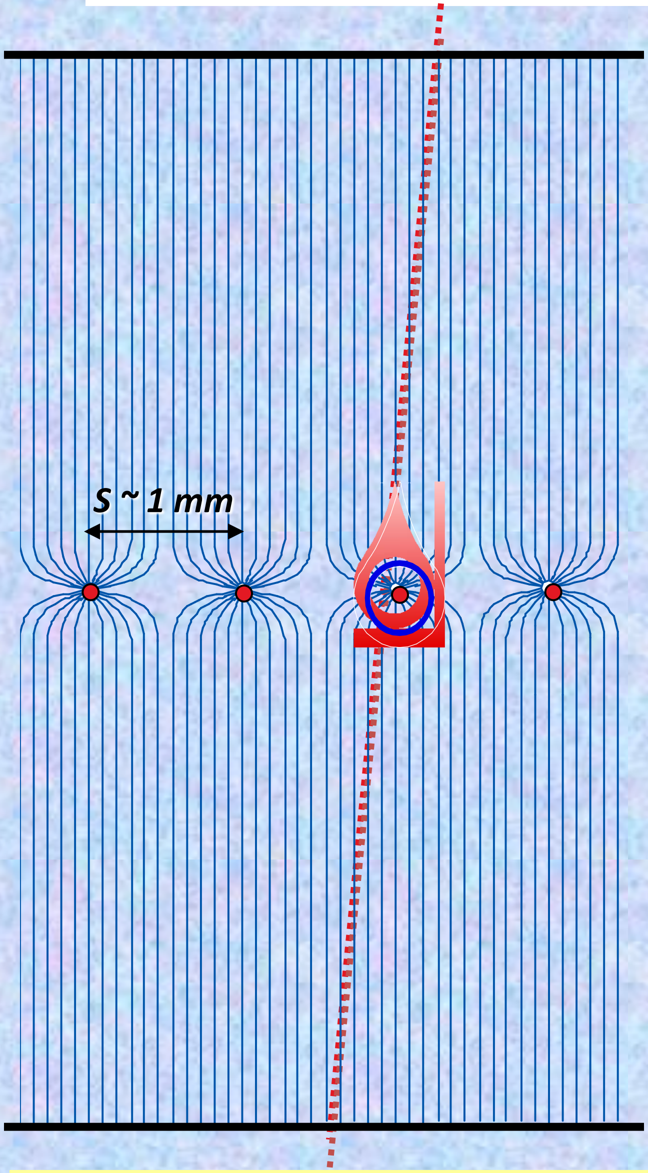


Time development of an avalanche in a proportional counter

A single primary electron proceeds towards anode in regions of increasingly high fields, experiencing ionizing collisions; due to the lateral diffusion, a drop-like avalanche, surrounding the wire develops.

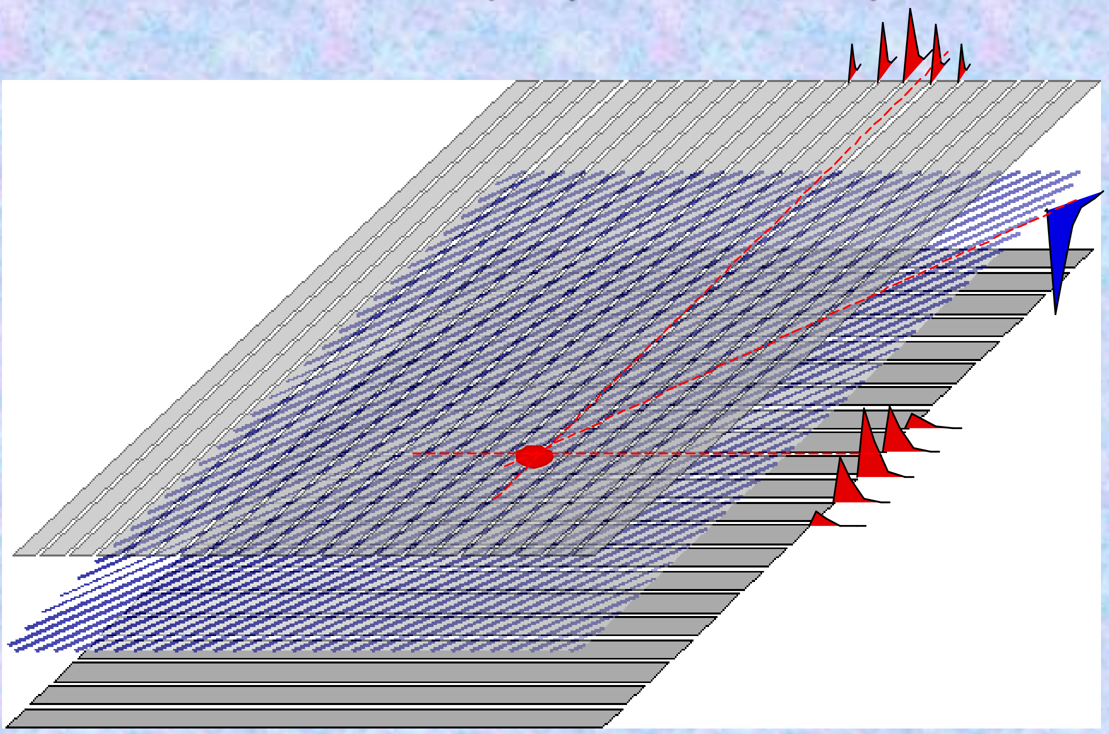
Moving charges create signal on nearby electrodes – the electron induced signal is almost negligible !!!

Multi-Wire Proportional Chamber (MWPC)



High-rate MWPC with digital readout:
Spatial resolution is limited to $s_x \sim s/\mathrm{sqrt}(12) \sim 300\ \mu m$

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)

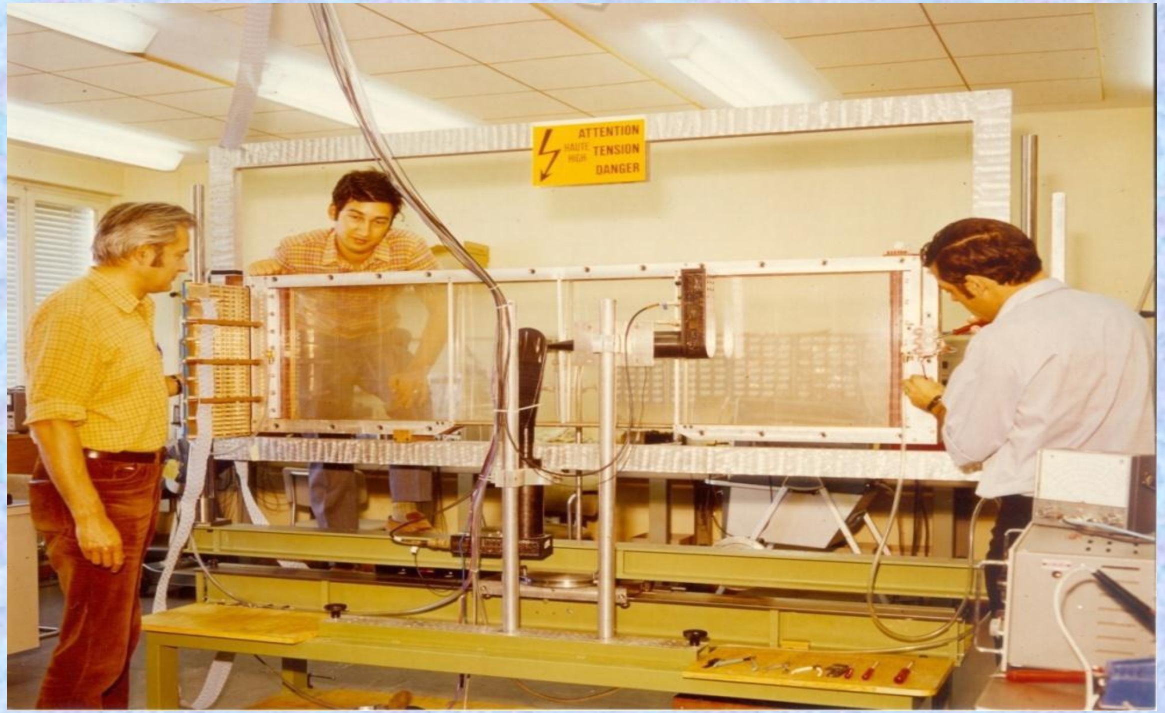


Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

Resolution of MWPCs limited by wire spacing
better resolution → shorter wire spacing → more (and more) wires…

Multi-Wire Proportional Chamber (MWPC): Electronics Imaging Devices

Gaseous proportional tracking detectors that revolutionized High Energy Physics



Georges Charpak with Fabio Sauli et Jean Claude Santiard

The 1st "Large Wire Chamber"…

The invention revolutionized particle detection, which passed from the manual to the electronic era.

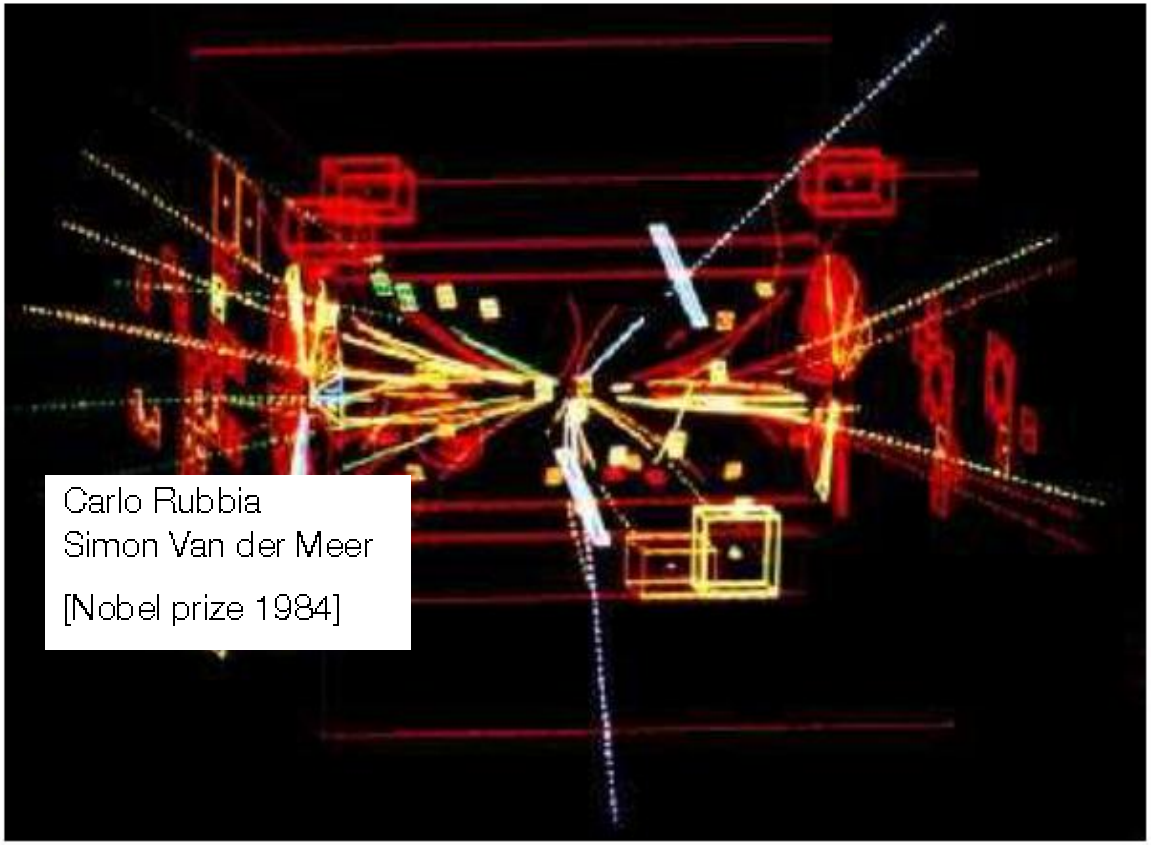
(1968 by Georges Charpak; Noble Prize 1992)

"Enormous Wire Chambers": Wide-Spread Tool in HEP for > 40 Years

W, Z - Discovery at UA1/UA2 (1983)

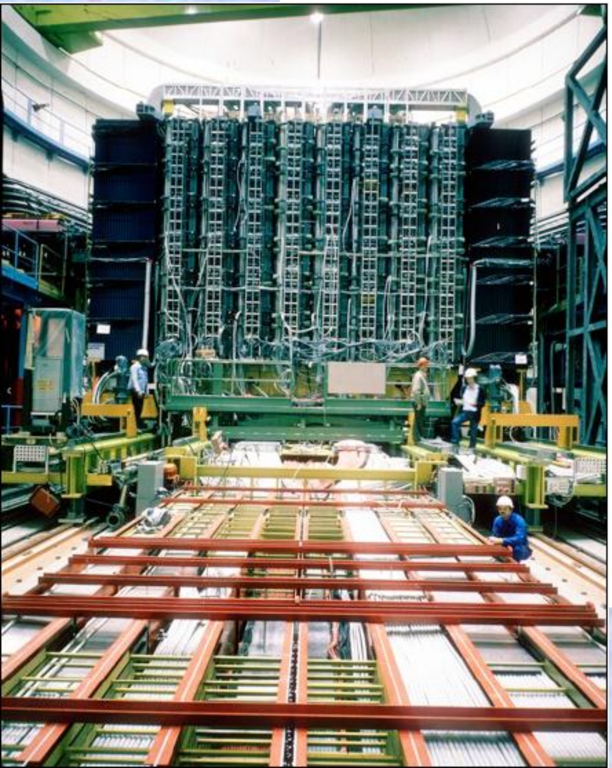
UA1 used a very large wire chamber.

Can now be seen in the CERN Microcosm Exhibition



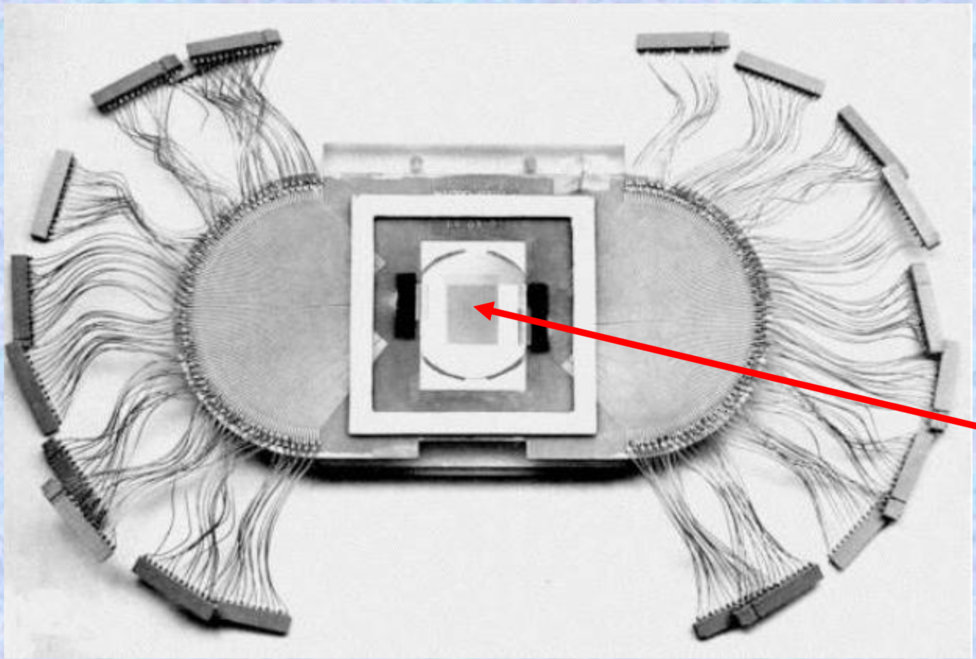
Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]



This computer reconstruction shows the tracks of charged particles from the proton-antiproton collision. The two white tracks reveal the Z's decay. They are the tracks of a high-energy electron and positron.

Silicon Detectors transformed the way we looked at the particles



First Silicon Strip Detector in HEP (1983): Experiment NA11/NA32 (CERN)

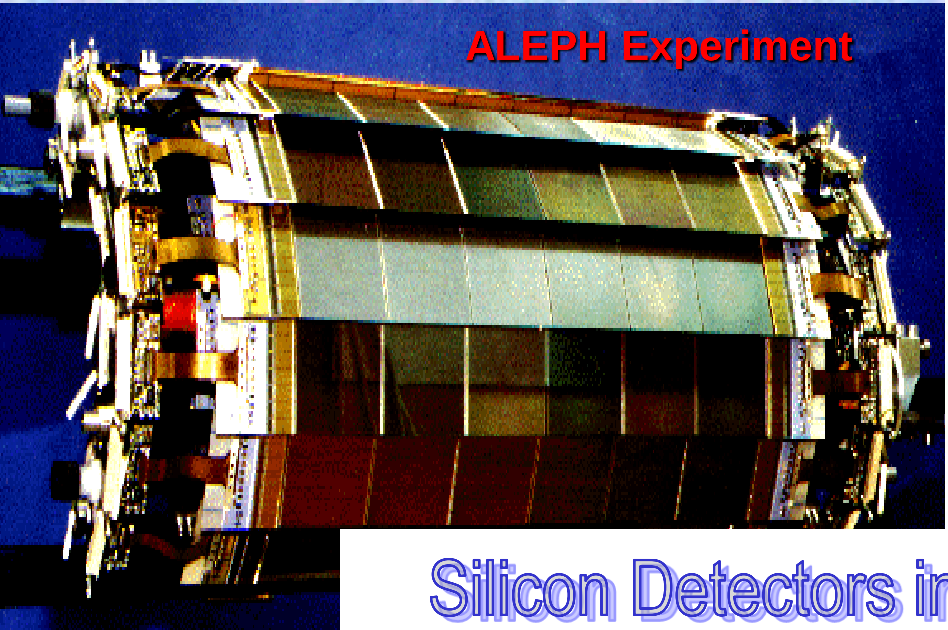
Goal: Measure lifetime and mass of the charm mesons D0, D-, D+, D+s, Ds

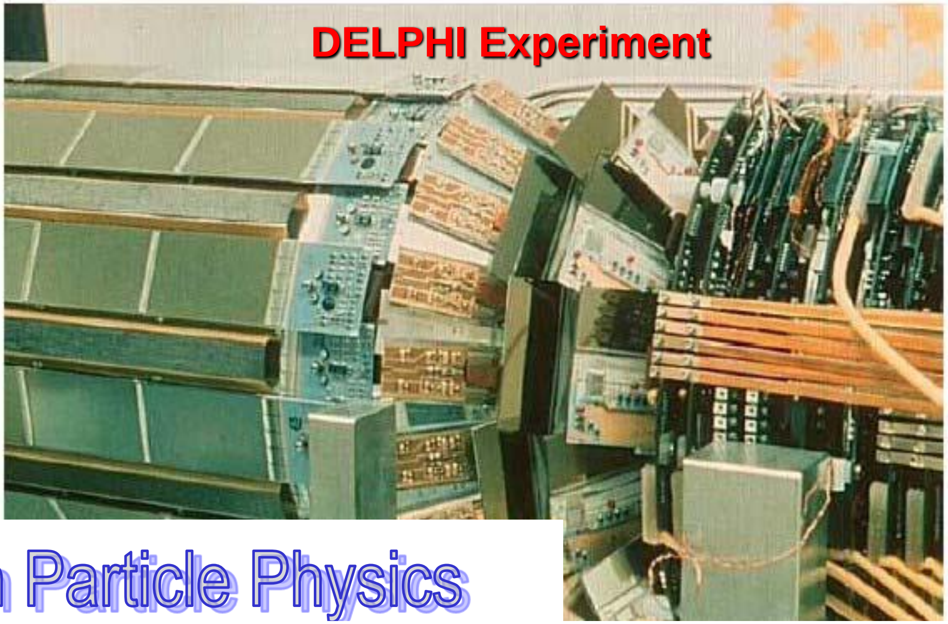
Ratio of detector surface to nearby electronics surface 1:300 !

Why silicon detectors ? They have a high density →
- **Large energy loss in a short distance**
- **Diffusion effect is smaller than in gas detectors, resulting in achievable position resolution of less than 10 μm**

Why silicon detectors ? <u>They allow vertex reconstruction →</u>
- **identify – tag – heavy quarks (b-, c-quarks)**
- **measure lifetimes**
- **mixing background suppression**

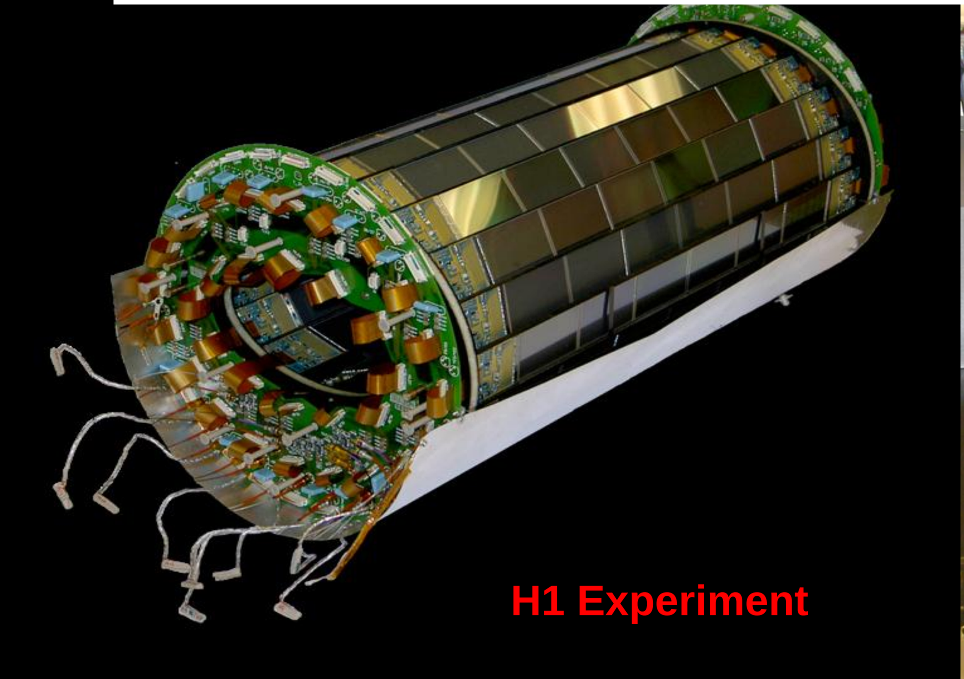
…… a lot of great physics!

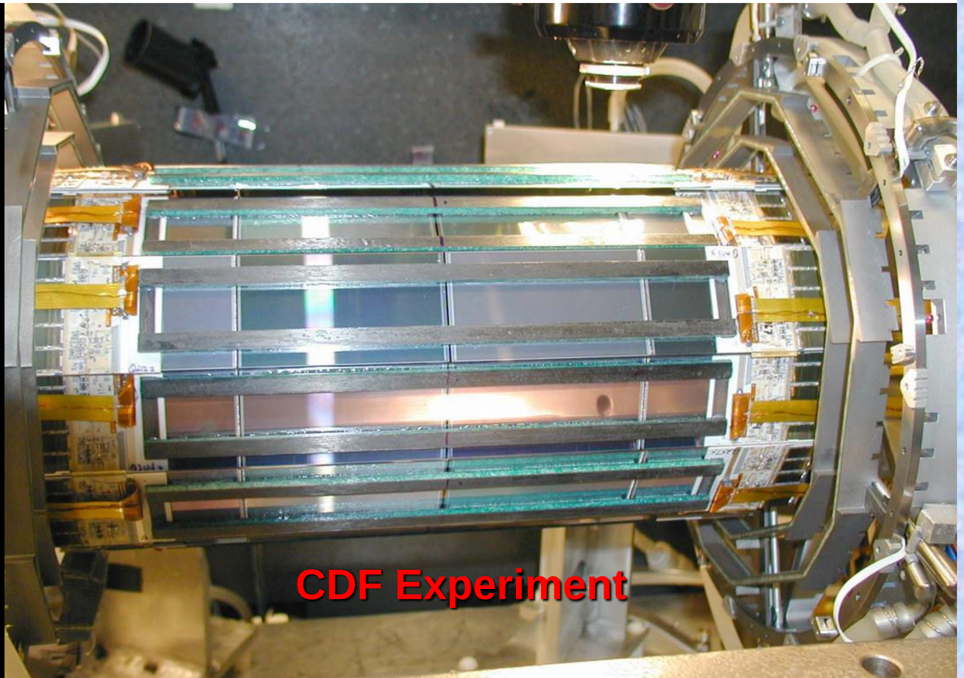

ALEPH Experiment


DELPHI Experiment

Silicon Detectors in Particle Physics

Strip and hybrid pixel detectors are mature technologies employed in almost every experiment in high energy physics.


H1 Experiment

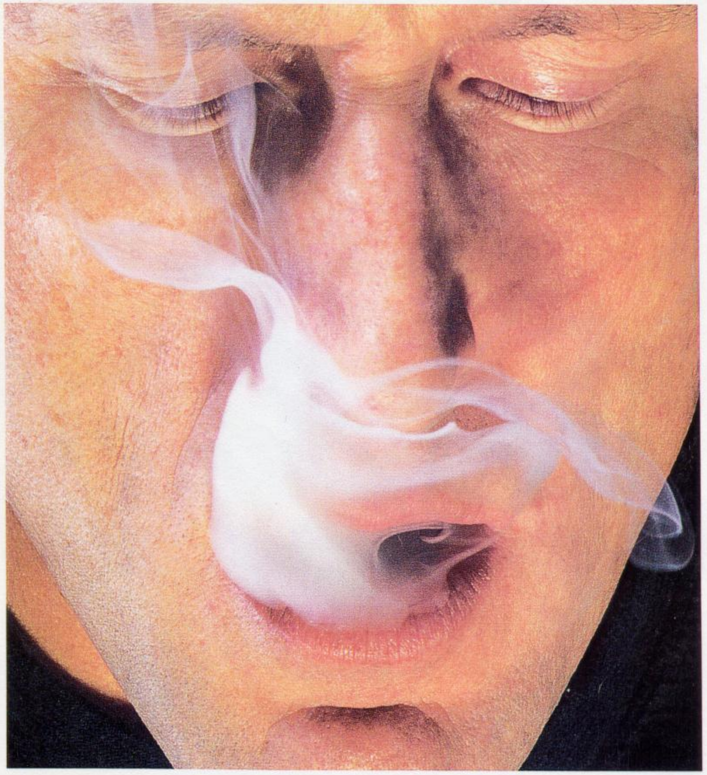

CDF Experiment

SCIENTIFIC AMERICAN

MAY 1995

$3.95
U.K. £2.75

What found the top quark.
Archaeology in peril.
The Niels Bohr mysteries.

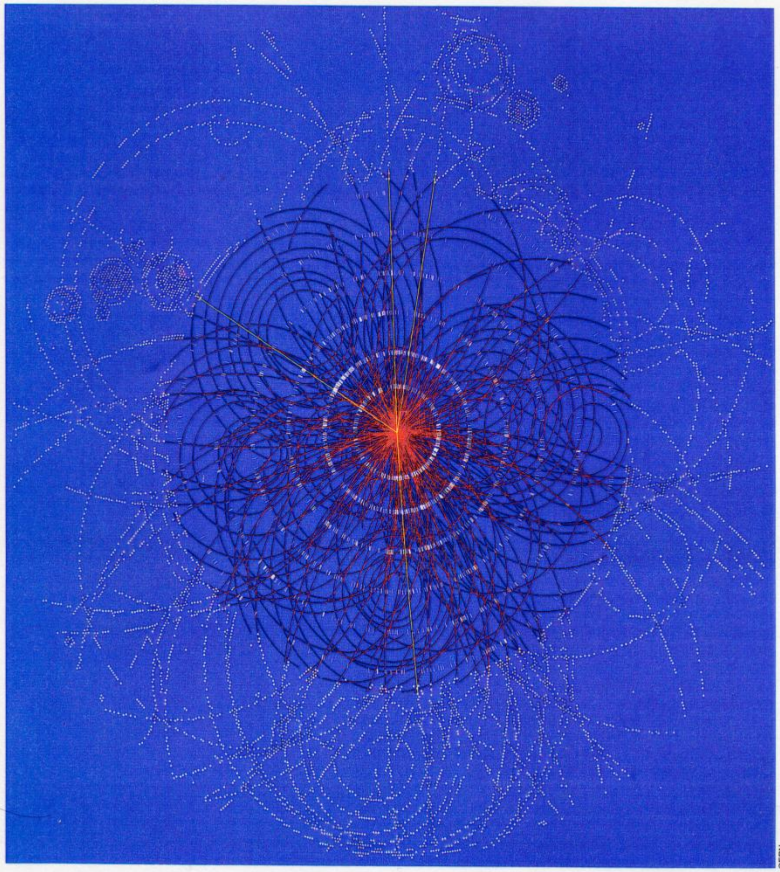


***Clouds** of tobacco smoke continue their spread, despite warnings.*

The Silicon Microstrip Detector

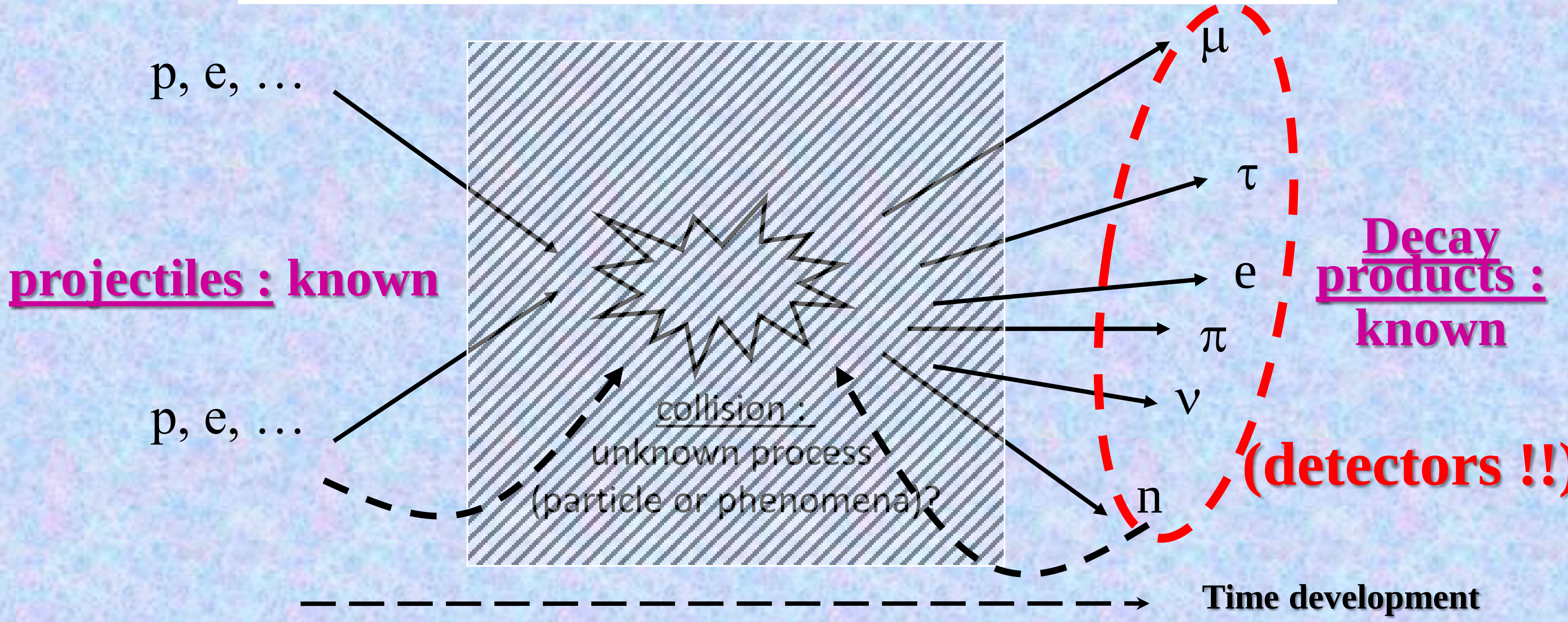
Produced with the same tools used to create integrated circuits, these detectors recently helped to find the top quark and are central to other crucial experiments

by Alan M. Litke and Andreas S. Schwarz



CERN

HEP Experiments: Simplified Picture



Ingredients for typical experiment :

- Find a nice region and build an accelerator there
- Design and build the detectors around BX points
- Add :
  - FE electronics, Trigger and DAQ, Control system, ...
- Requirement to all the ingredients correlated (more often anti-correlated ☹)

Which particles do we see in the detector

«Truly » elementary particles :

Z^0, $W^{+/-}$, H decay before they reach active part of the detector

Invisible : *jets*

Leptons spin = 1/2		
SAVEUR	masse GeV/c²	Charge électriq.
ν_e neutrino électron.	$<1\times10^{-8}$	0
e électron	0.000511	–1
ν_μ neutrino muon	<0.0002	0
μ muon	0.106	–1
ν_τ neutrino tau	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
SAVEUR	masse GeV/c²	Charge électriq.
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

force électrofaible spin = 1		
Nom	Masse GeV/c²	charge électriq.
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

interaction forte spin = 1		
Nom	Masse GeV/c²	charge électriq.
g gluon	0	0

+ Higgs

+ Super-Symmetric partners ?

Neutrinos ν_i can be seen in the dedicated detector only, or sometimes indirectly. Probability of interaction $P_{Int.}$ with matter is small.

Free quarks have not been observed.

Quarks form hadrons : mesons ($q\bar{q}$) or baryons (qqq).

cf. QCD

« Initial » (diagram) quarks can be probed via measurement of jets.

Examples : $\pi^{+/-}$, p, n, $K^{+/-}$, etc.

Which particles do we see in the detector

Directly, we measure kinematics of the following particles :

e^+, e^-, γ

proton **p** (quarks de valence : uud + g +…)

neutron **n** (udd+g+…)

μ^+, μ^- : given Lorentz boost ($\gamma\beta c\tau$) is sufficient !

π^+, π^- : given Lorentz boost is sufficient !

K+, K- : given Lorentz boost is sufficient !

Particular case : ν « seen » by the missing energy technique $\not{E}$
(for collider experiment only)

Most of the particles are reconstructed via their decay products :

τ, Z^0, $W^{+/-}$, Higgs, etc

$\pi^0 \longrightarrow \gamma\,\gamma$ ($\pi^0 = (u\bar{u}-d\bar{d})/\sqrt{2}$)

Baryons and mesons (charm and beauty hadrons, etc…)

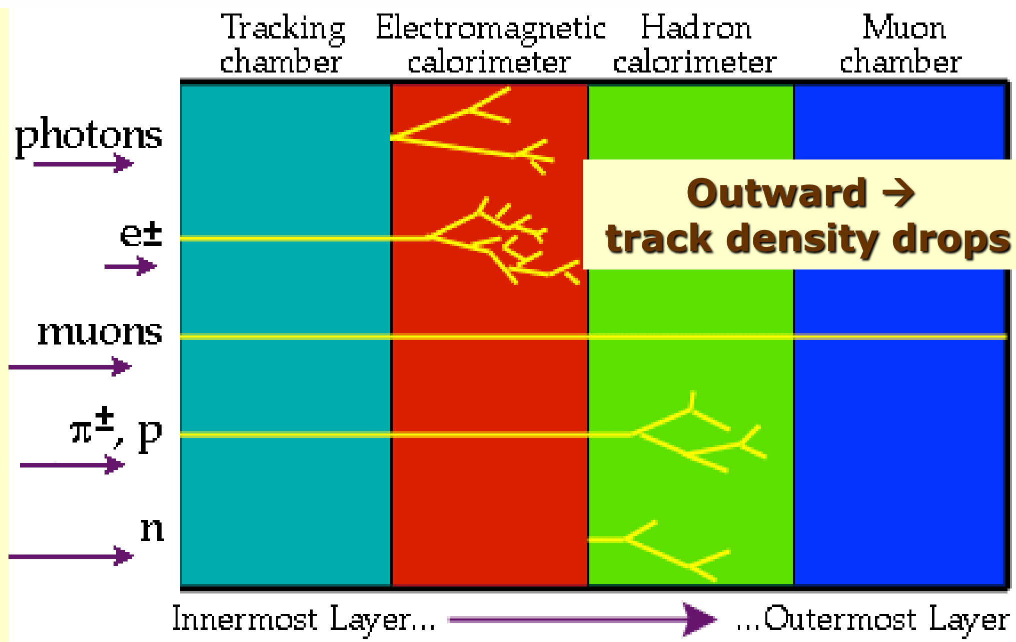
Particular case : *jets* of particles ; gives information on the « early » quark/gluon, from primary interaction, accessible as hadrons at the later stage.

Particle Physics Detectors

- There is not one type of detector which provides all measurements we need -> “Onion” concept -> different systems taking care of certain measurement
- Detection of collision production within the detector volume

Fundamental parameters:

- **Charge**
- **Momentum**
- **Decay products**
- **Life time**
- **Decay vertex**
- **Mass**
- **Spin**
- **Energy**



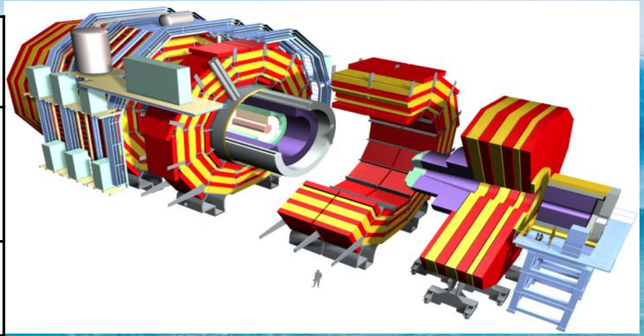
Tracker: Momentum of charged particles due to magnetic field and precise measurement of track

Calorimeter: Energy measurement of photons, electronics and hadrons through total absorption

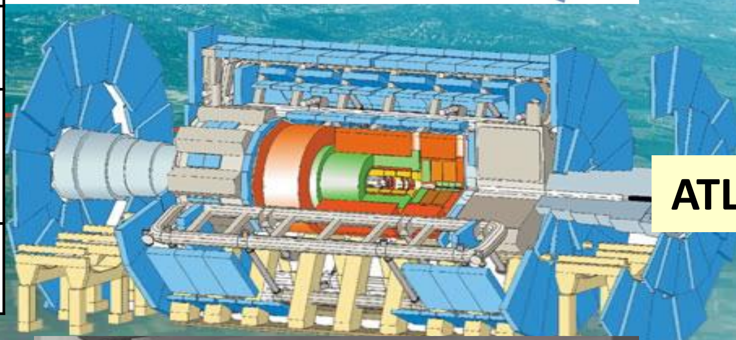
Myon-Detectors: Identification and precise momentum measurement of myons outside of the magnet

The Large Hadron Collider

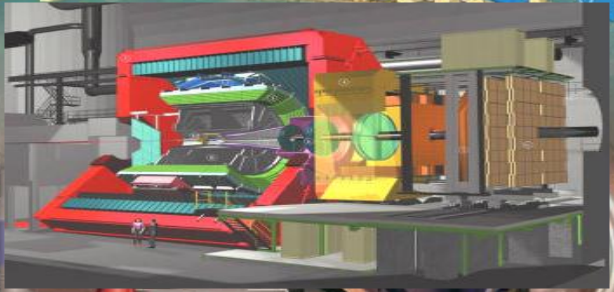
Nominal Settings	
Beam energy (TeV)	8 (14 from 2015)
Interaction rate (MHz)	40
# particles per bunch	1.15×10^{11}
Luminosity ($cm^{-2}\ s^{-1}$)	10^{34} ($7*10^{33}$ -now)
Stored energy per beam	362 MJ



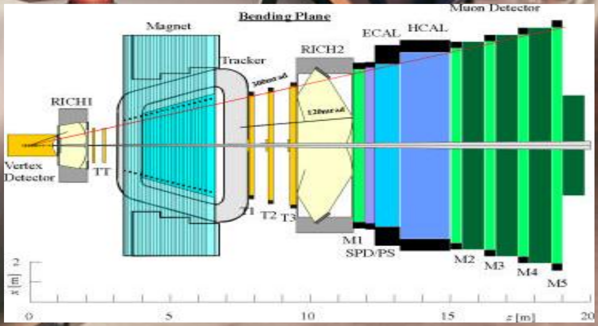
CMS



ATLAS

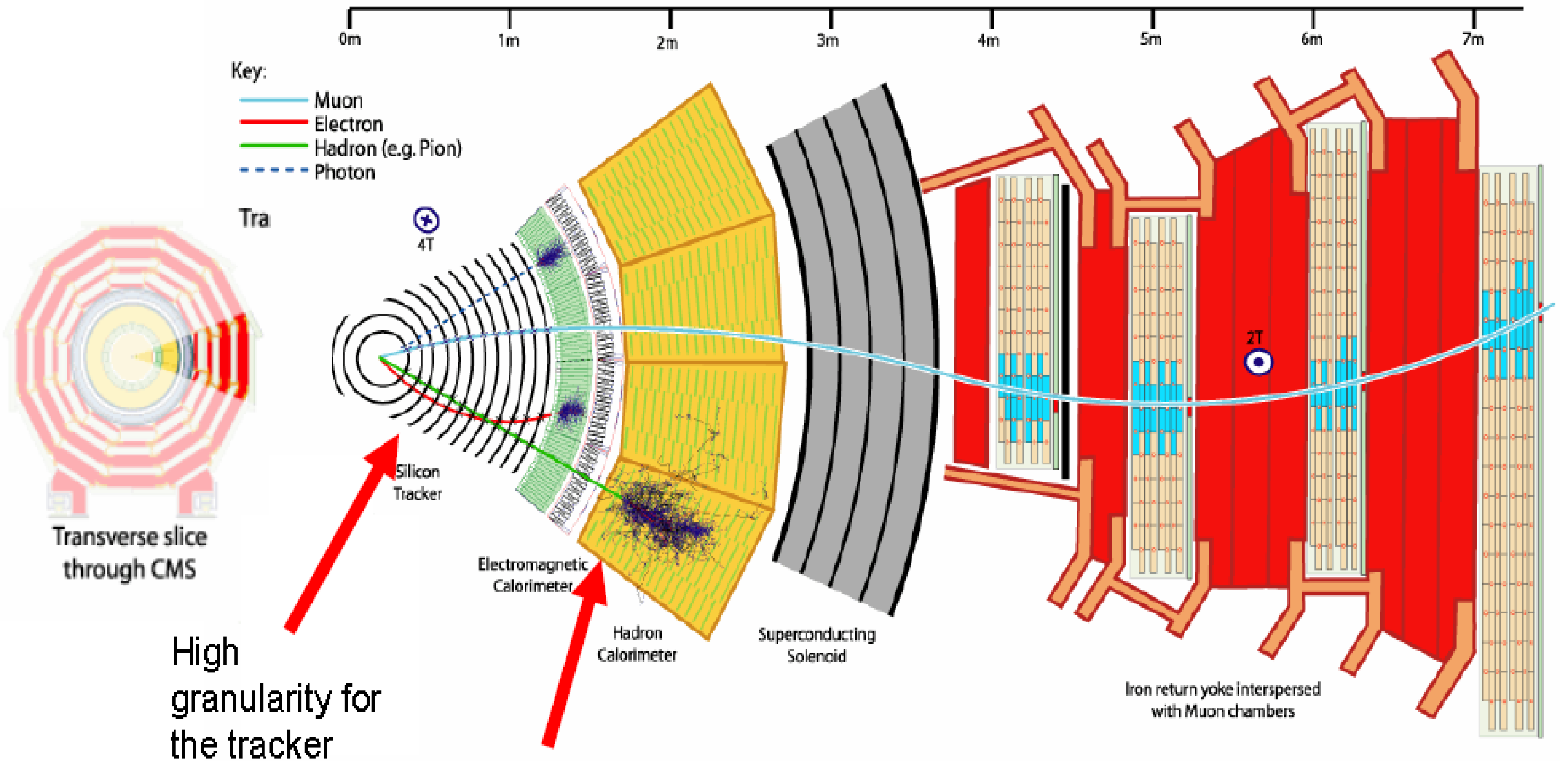


ALICE



LHCb

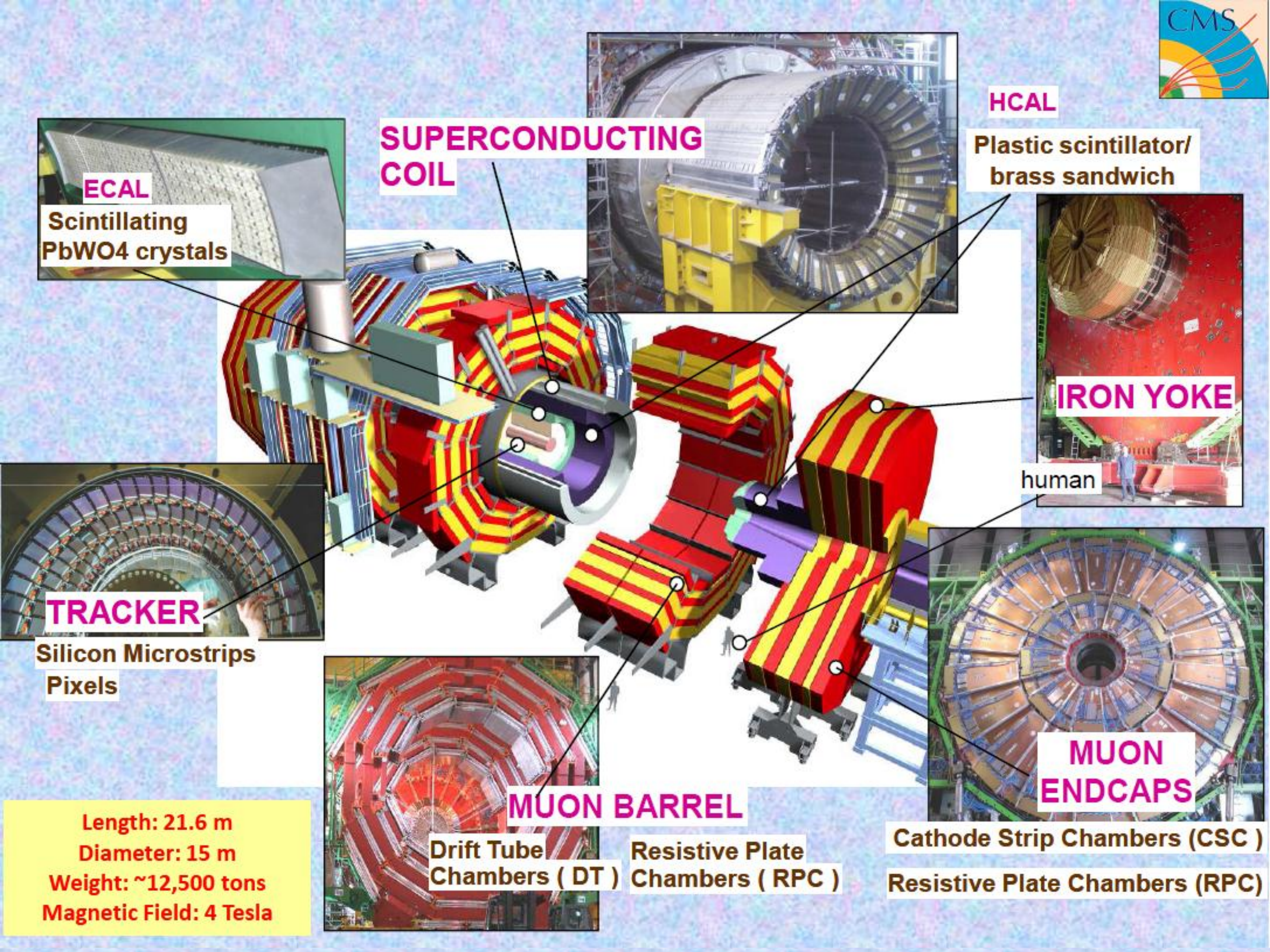
Collider Experiments: Detector Cross Section (e.g. CMS)



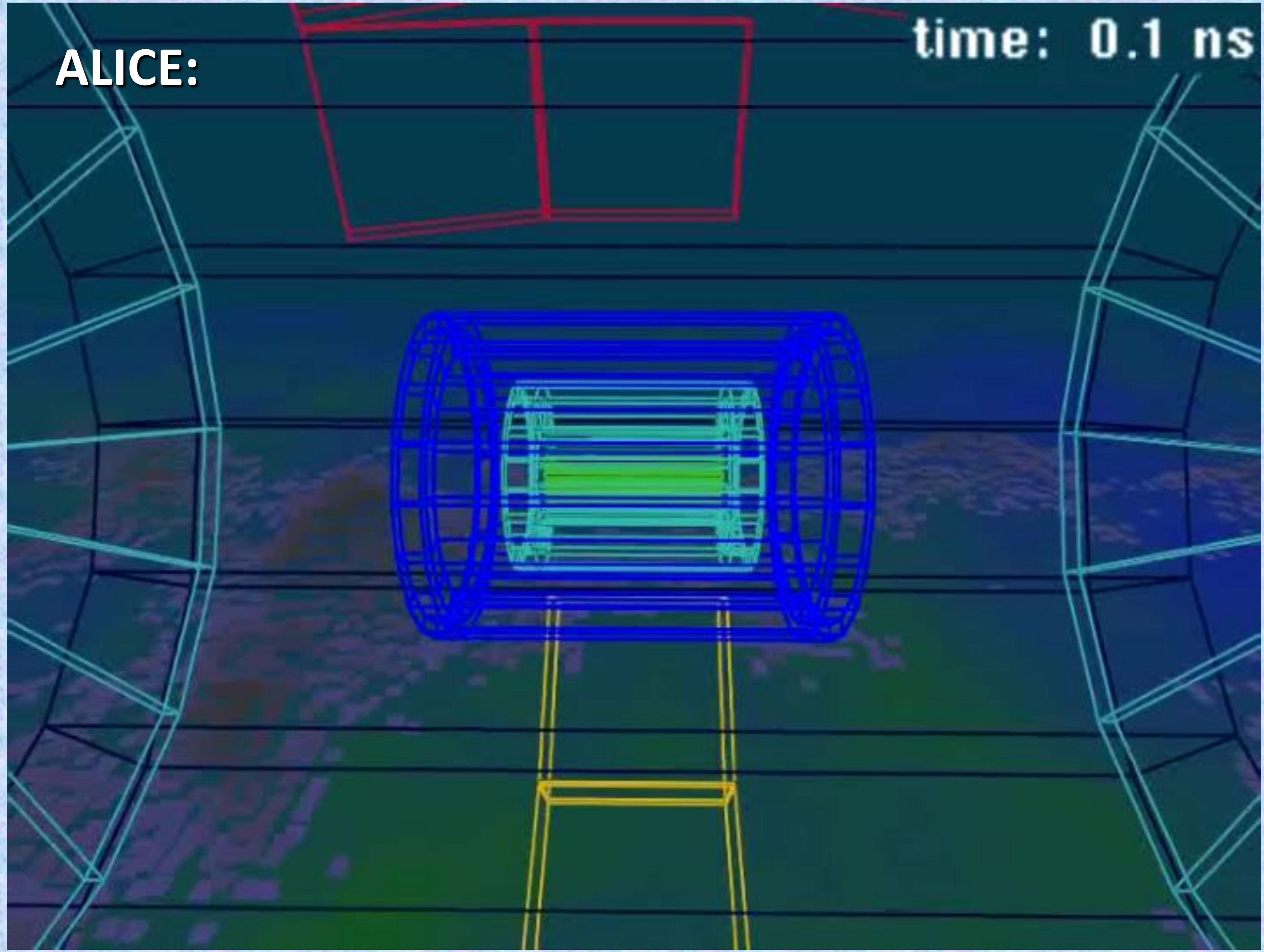
High granularity for the tracker (high occupancy)

Good energy resolution up to highest energies

Radiation hard (hadron collider)


CMS
HCAL
Plastic scintillator/
brass sandwich
SUPERCONDUCTING
COIL
ECAL
Scintillating
PbWO4 crystals
IRON YOKE
human
TRACKER
Silicon Microstrips
Pixels
MUON
ENDCAPS
MUON BARREL
Drift Tube
Chambers (DT)
Resistive Plate
Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
Length: 21.6 m
Diameter: 15 m
Weight: ~12,500 tons
Magnetic Field: 4 Tesla

Computer Simulated Event in LHC Experiment



LHC Experimental Challenge

LHC Detectors (especially ATLAS, CMS) are radically different from the ones from the previous generations

High Interaction Rate:

- pp interaction rate → 1 billion interactions/s
- Data can be recorded for only ~10^2 out of 40 million crossings/sec
- Level-1 trigger decision takes ~2-3 μs

⇨ electronics need to store data locally (pipelining)

Large Particle Multiplicity:

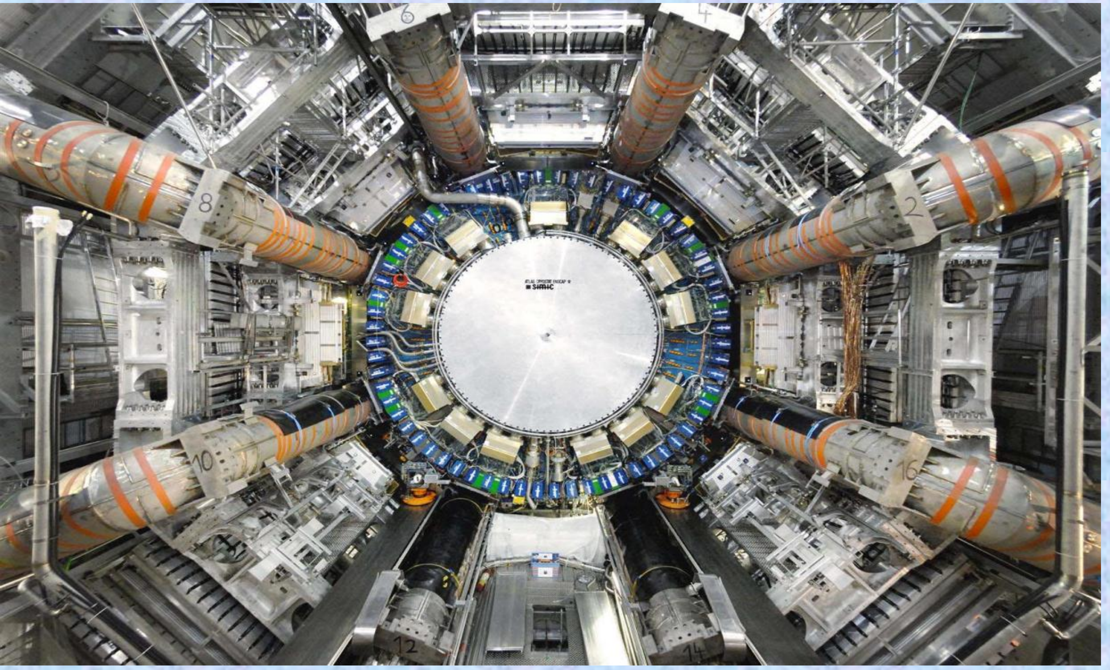
~ <20 -25 > superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
→ need highly granular detectors with good time resolution
→ large number of channels (~ 100 M ch)
→ need factor 10 better momentum resolution than at LEP

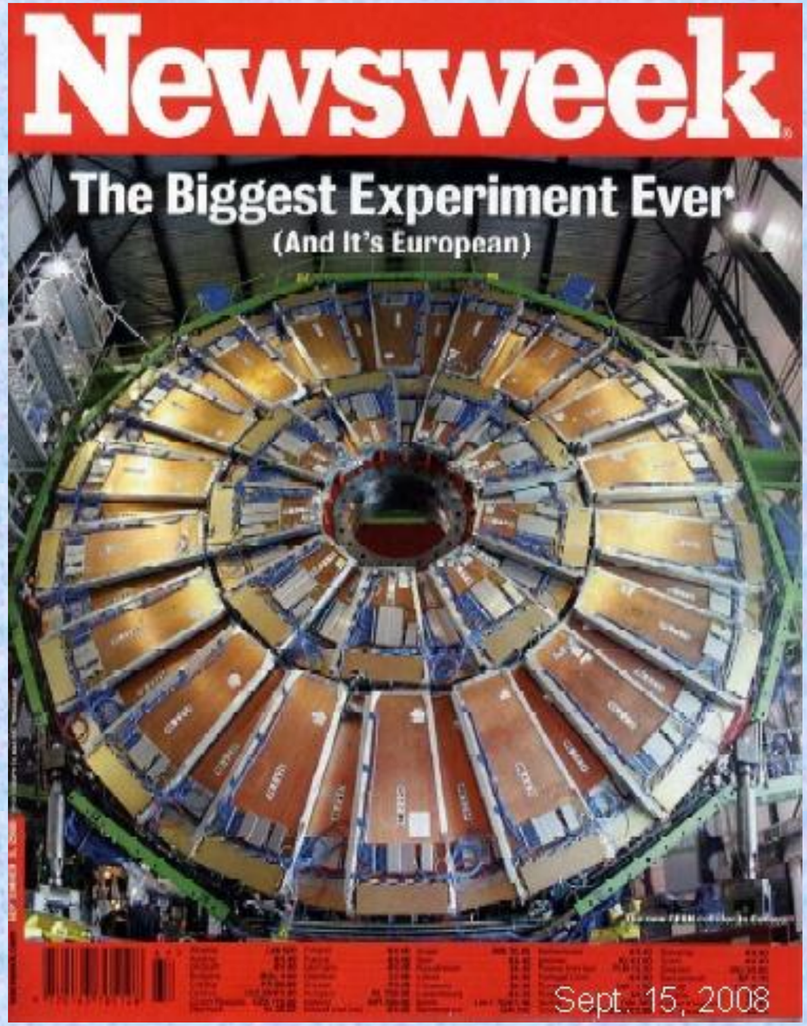
High Radiation Levels:

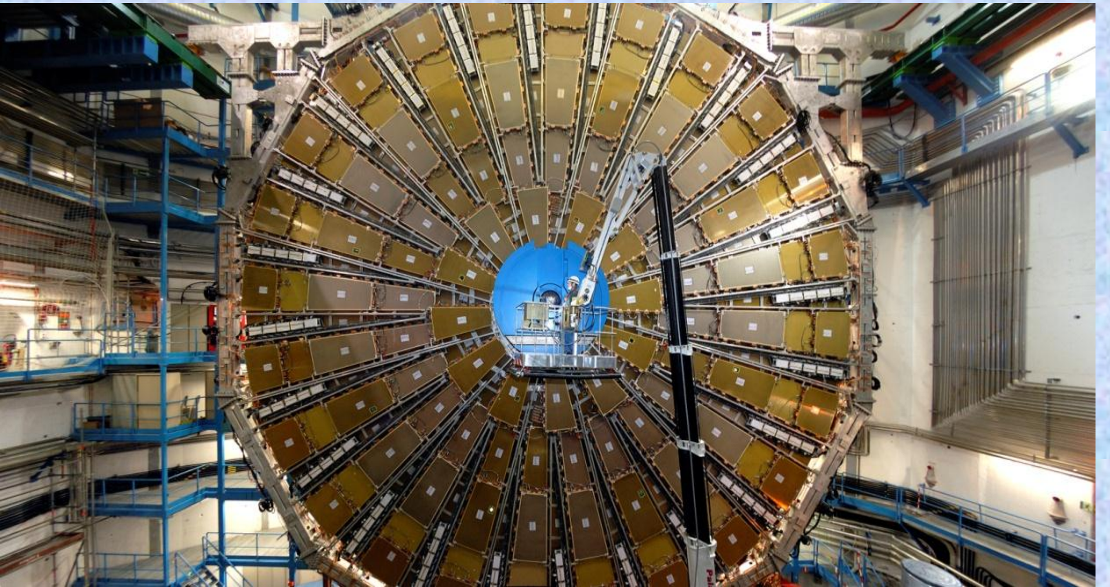
⇨ radiation hard (tolerant) detectors and electronics

LHC Detectors: Triumphs of Instrumentation

From basic ideas to complex detector systems →Design cycle of LHC > 20y!

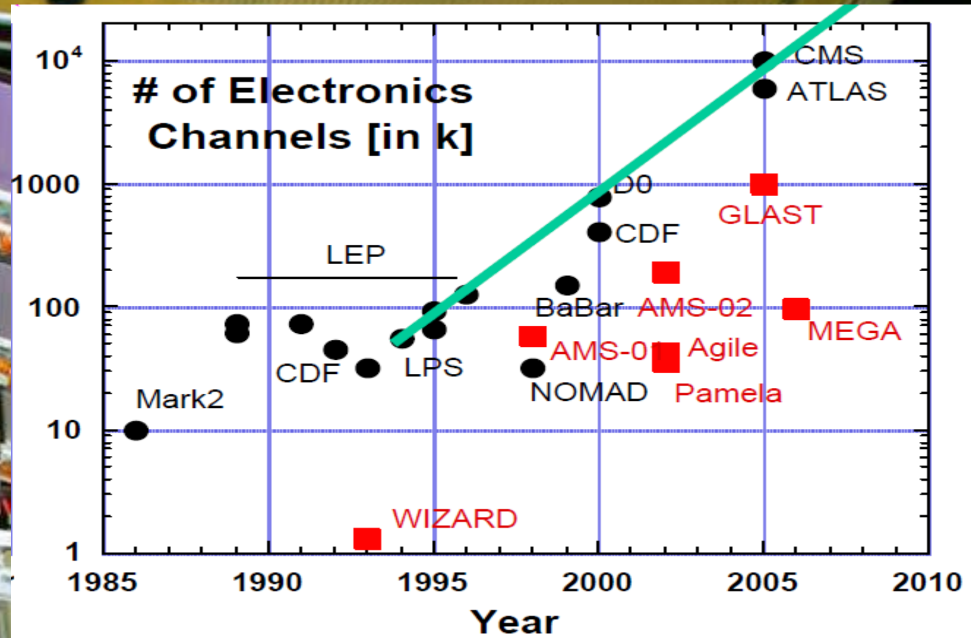


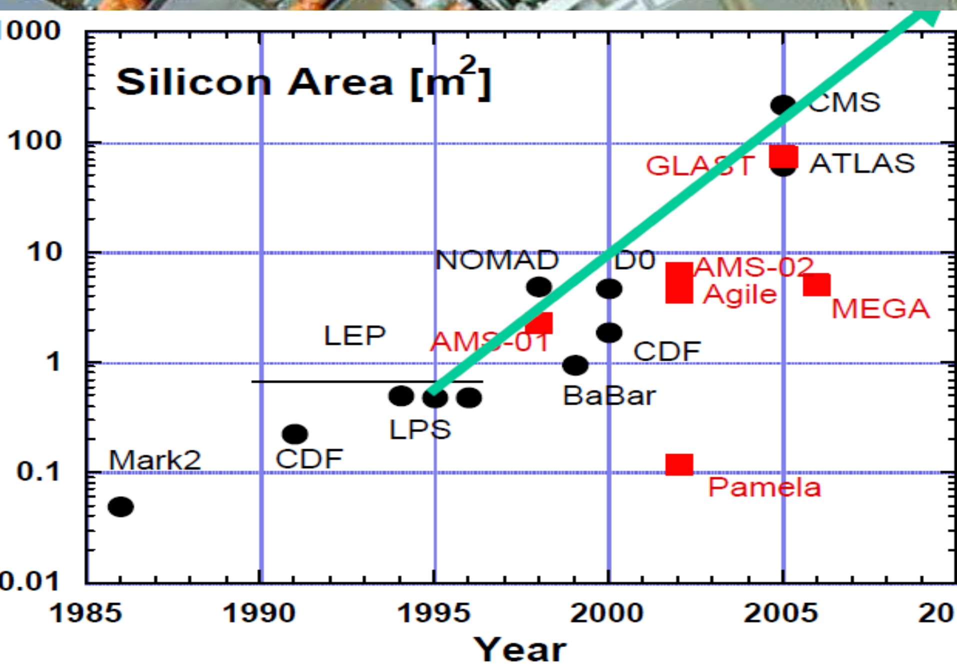


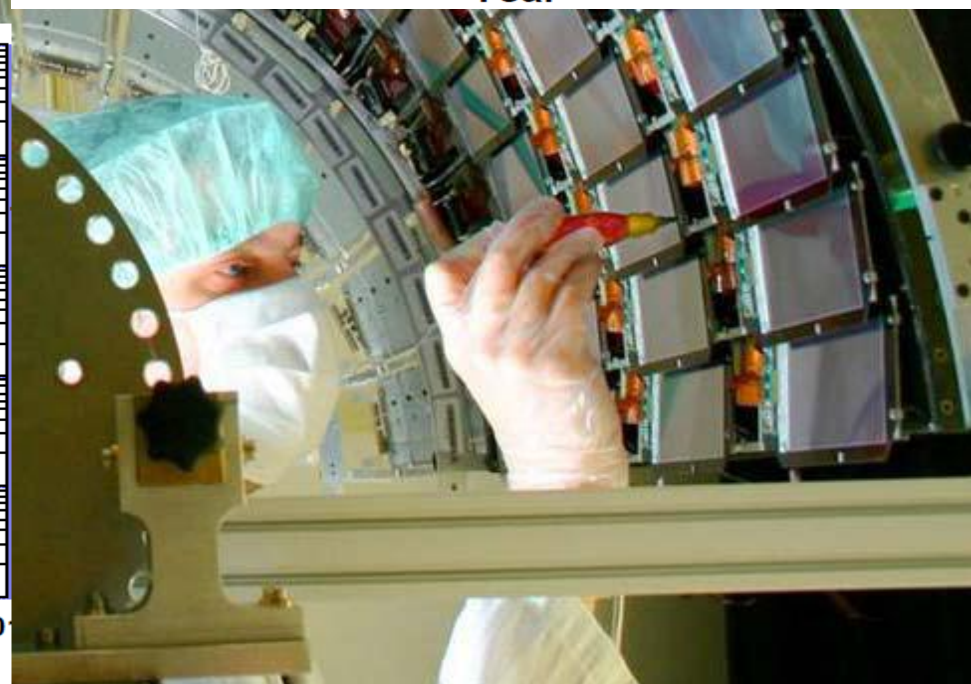


Digital Cameras the Size of Cathedrals

Silicon Detectors in Particle Physics: Evolution of Scale

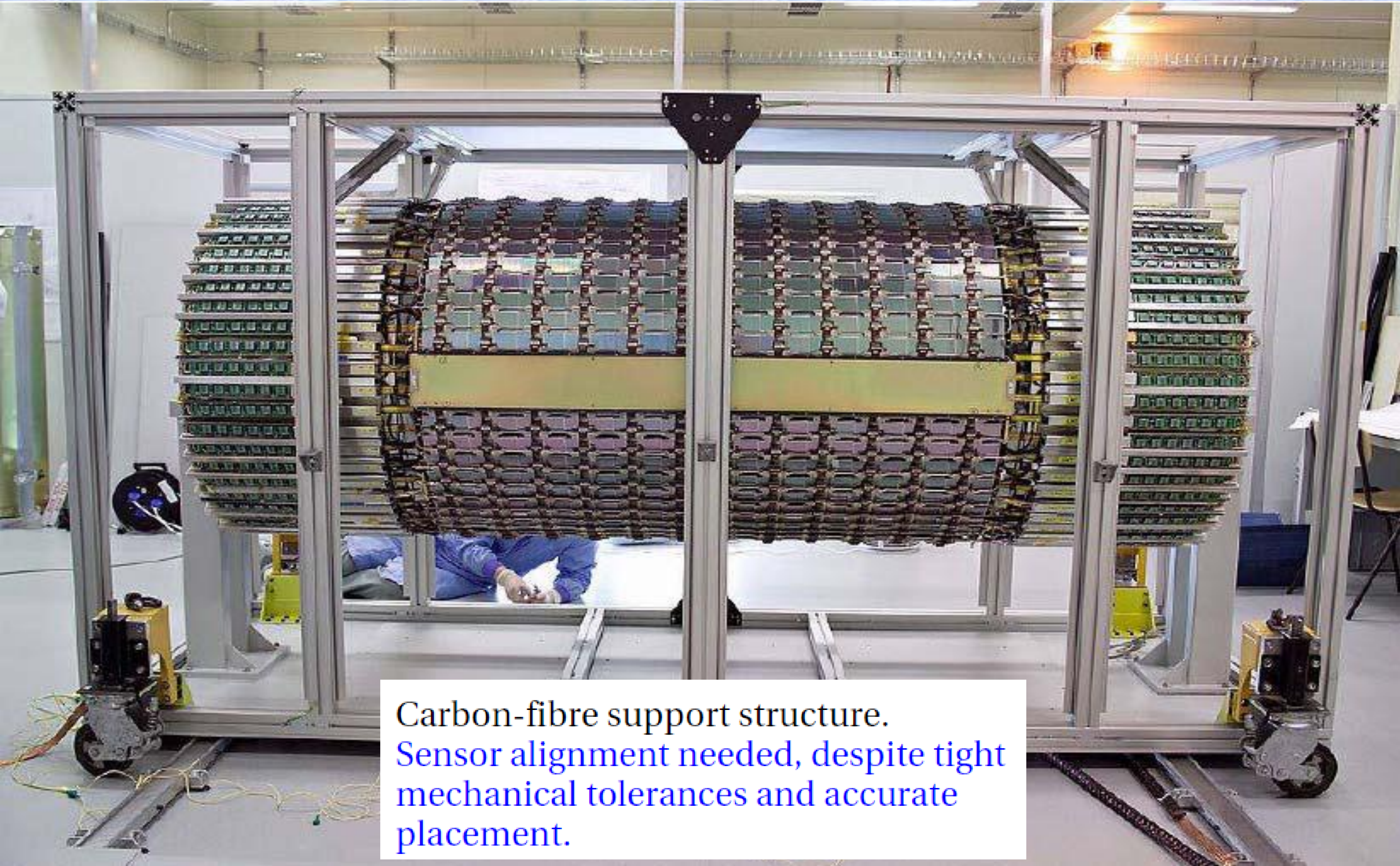






The ATLAS Inner Central Tracker (Barrel)

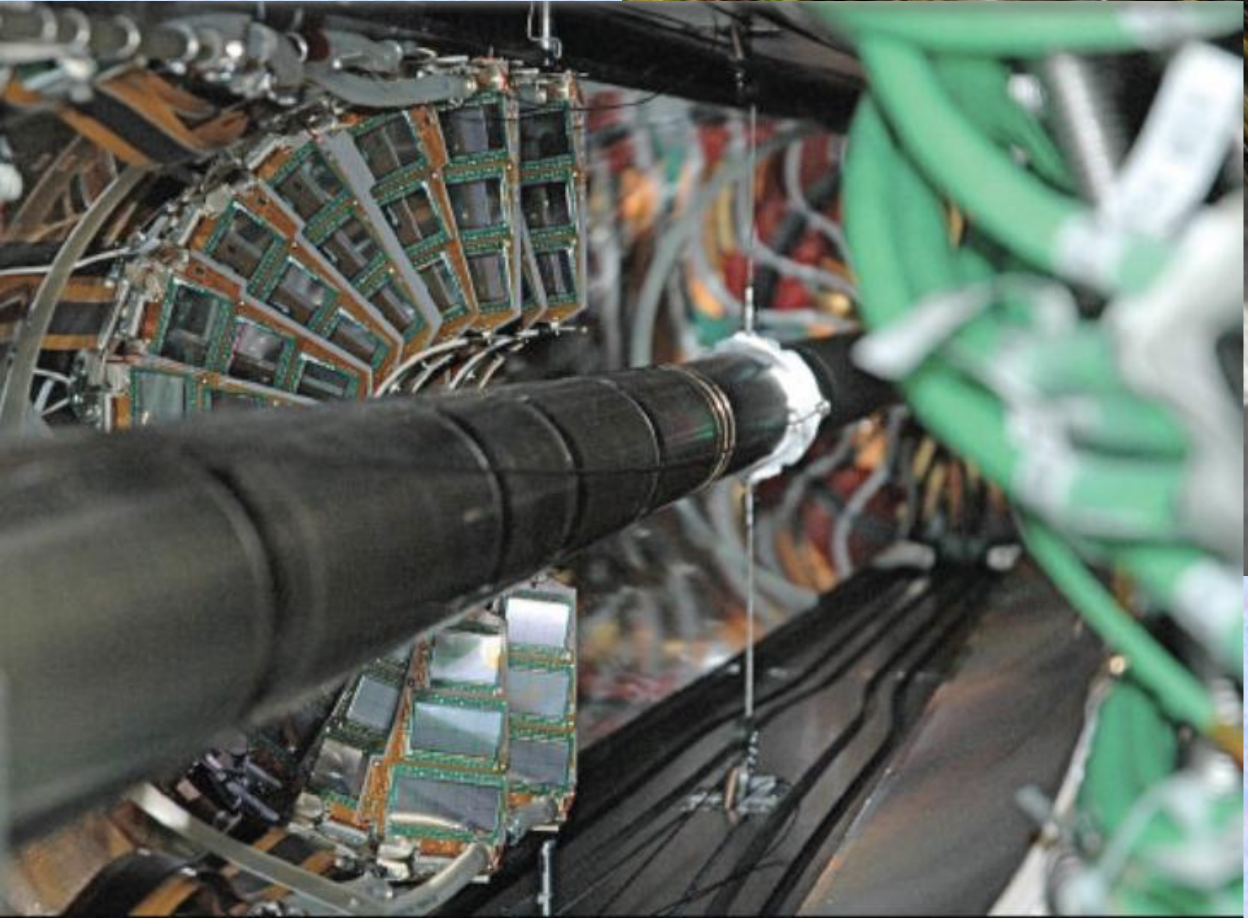
The most critical parts are the sensors, ASICs and system engineering (mechanics, power, cooling, assembly, etc) and integration

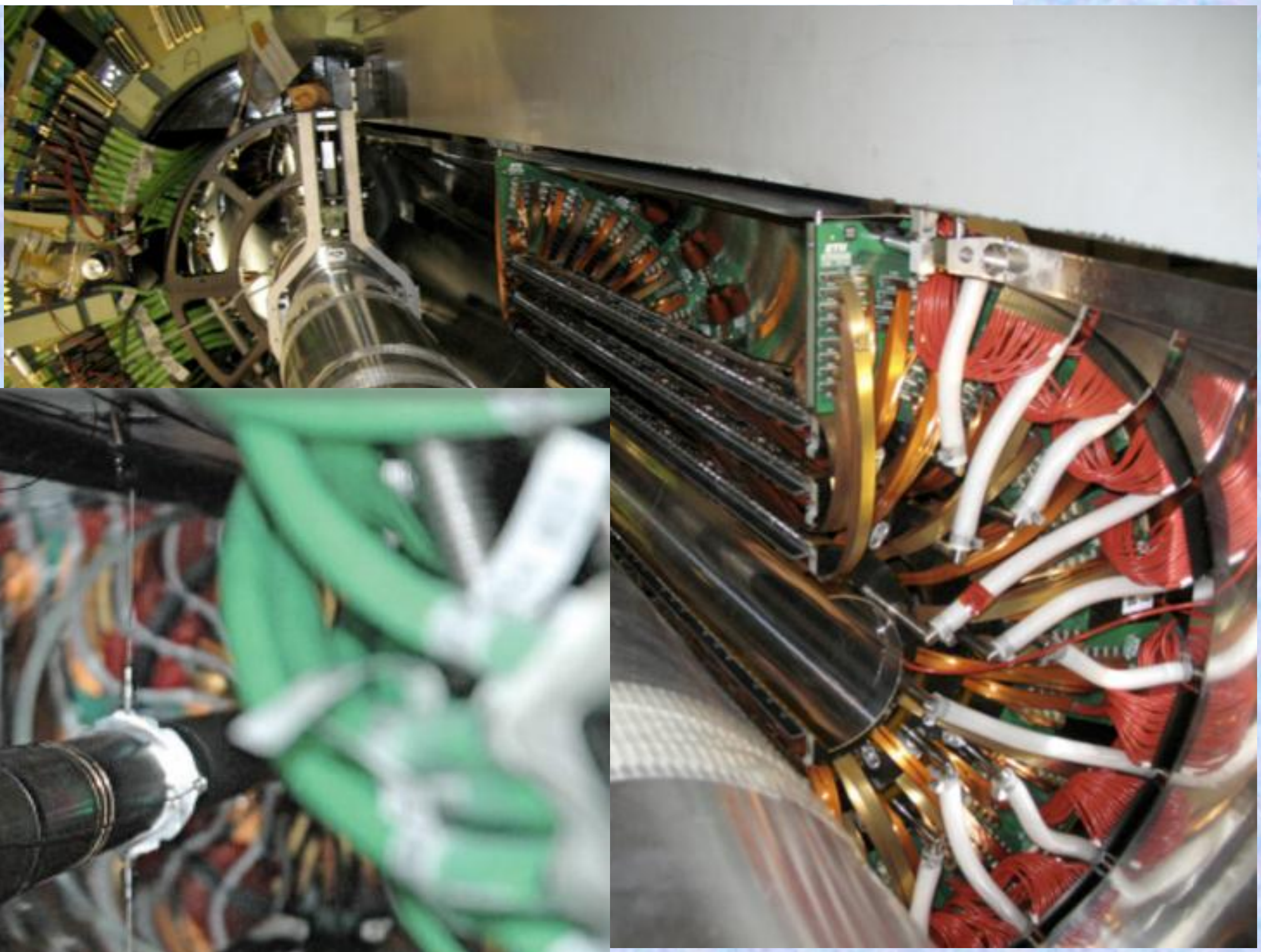


Carbon-fibre support structure.
Sensor alignment needed, despite tight mechanical tolerances and accurate placement.

The CMS Inner Tracker: Pixel Insertion

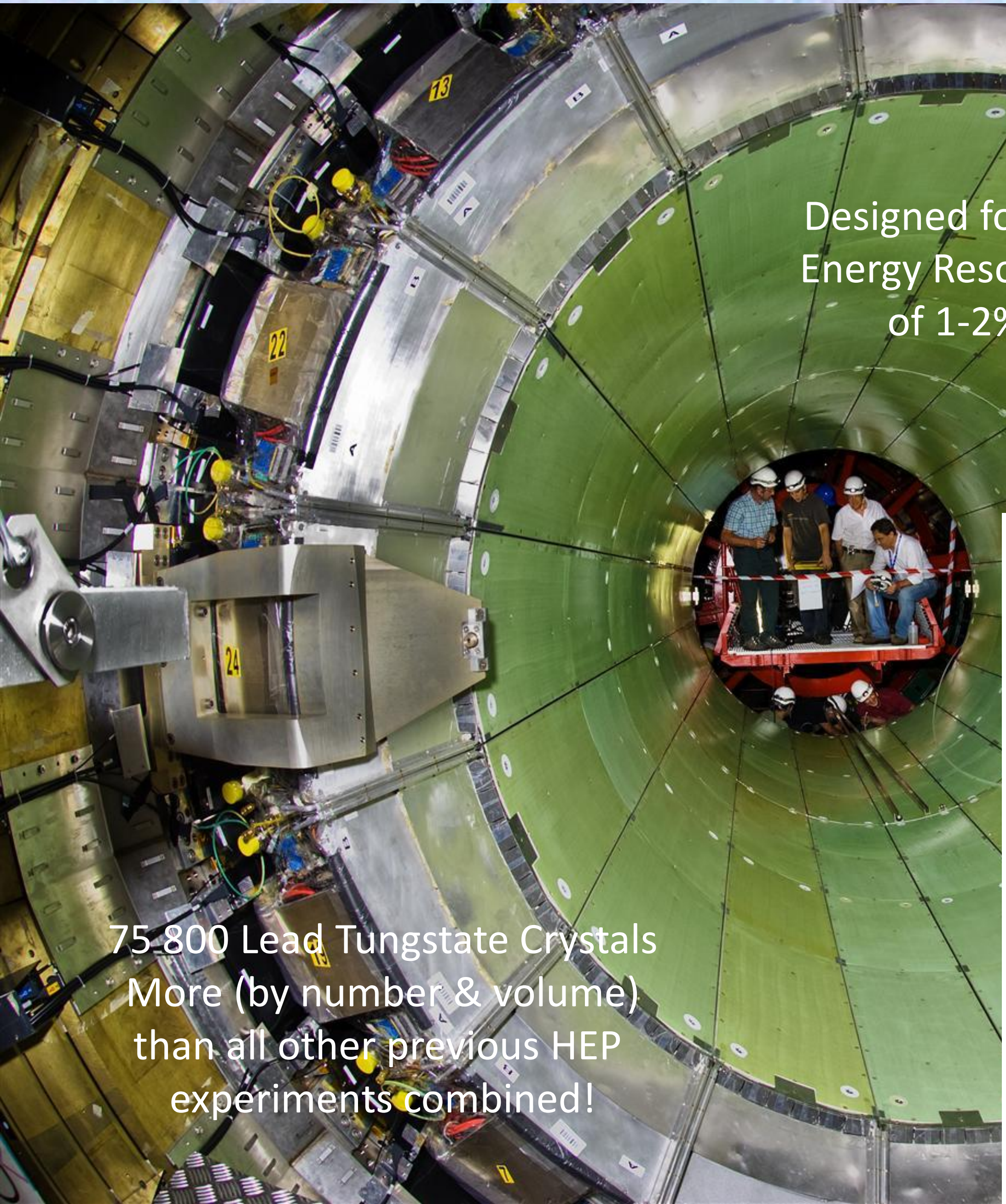
Barrel pixel





Forward pixel

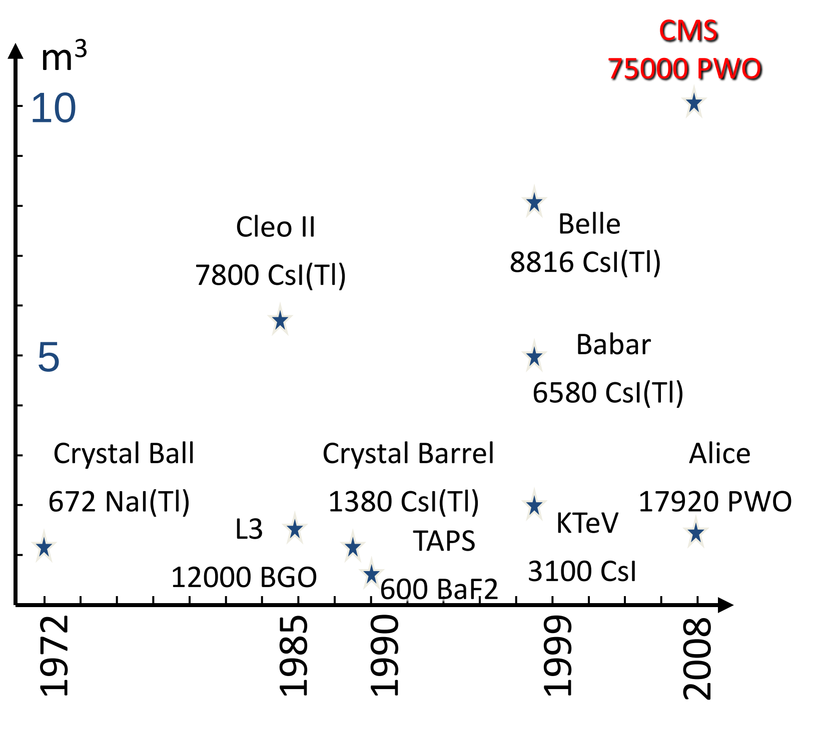
Electromagnetic Calorimeter



ECAL Barrel installed July 2007

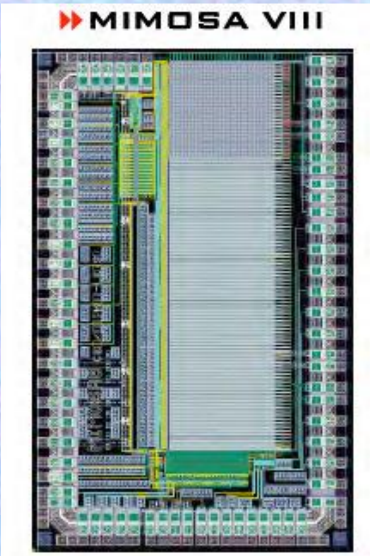
Designed for e/γ Energy Resolution of 1-2%

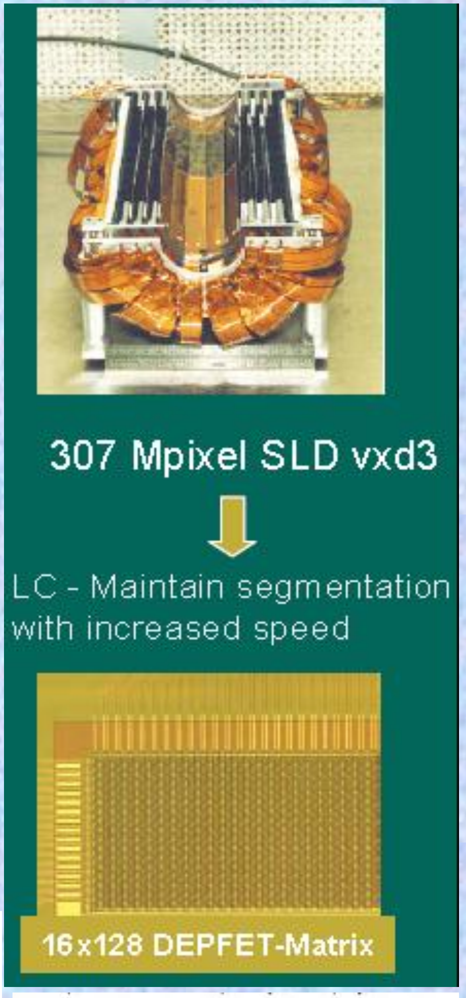
75 800 Lead Tungstate Crystals
More (by number & volume) than all other previous HEP experiments combined!

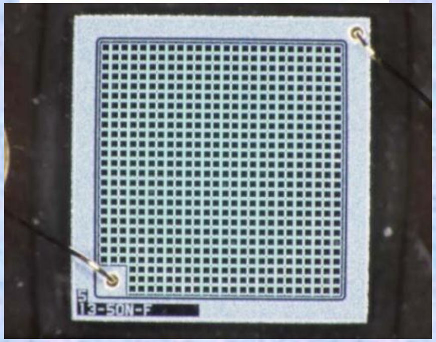


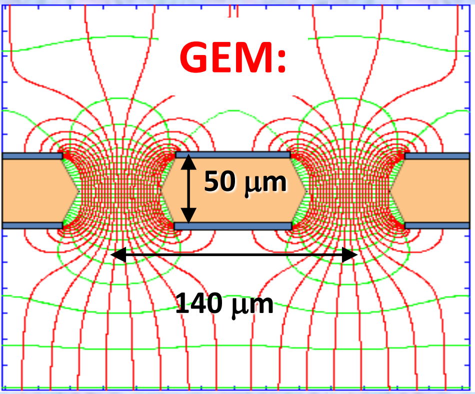
Trends in Technology Enable Advances in Detectors

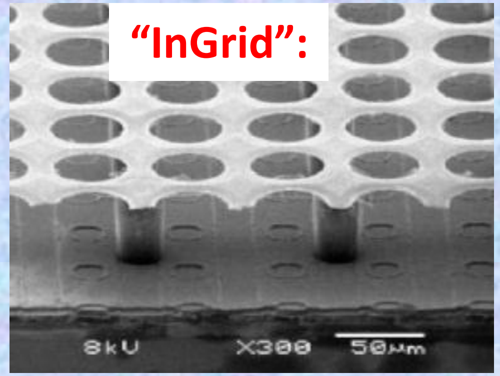
- **Segmentation**
  - Vertex elements with 20 μm and smaller pixels
  - Calorimetry employing silicon elements
  - Micro-Pattern Gaseous Detectors
- **Speed & Power**
  Faster electronics, low noise and low power
- **Integration**
  Microelectronics, mechanical complexity
- **Materials**
  Sensor, rad hard, robust, thin
- **Radiation immunity**
  Understanding, design, annealing

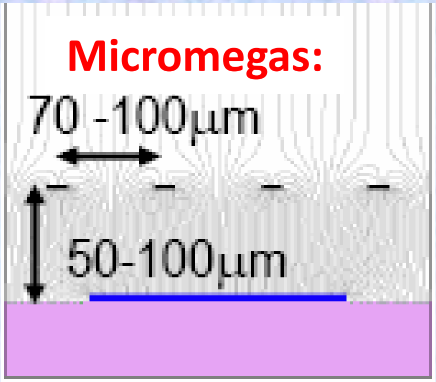


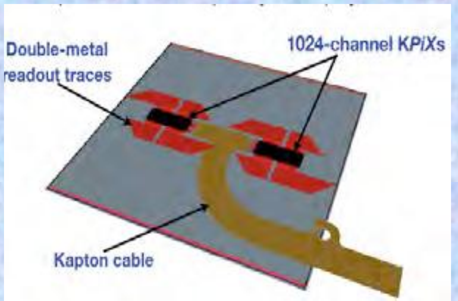




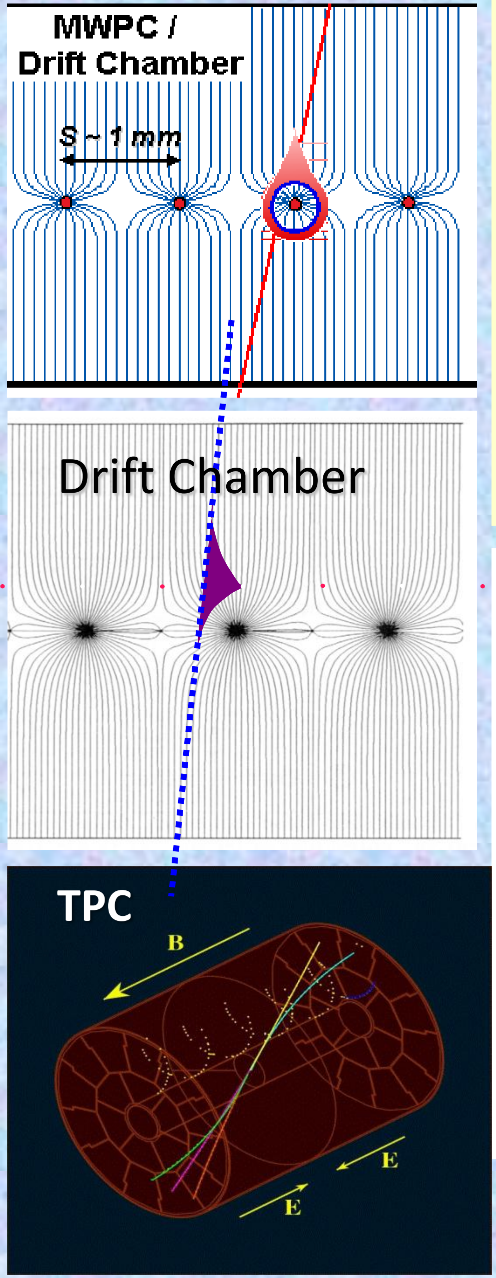








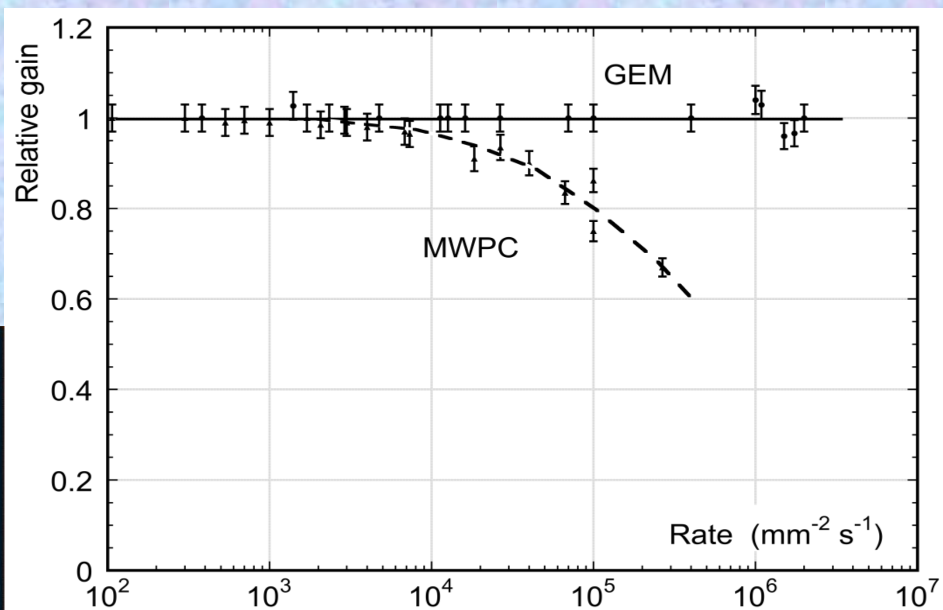
RD51 Collaboration: Micro-Pattern Gaseous Detectors



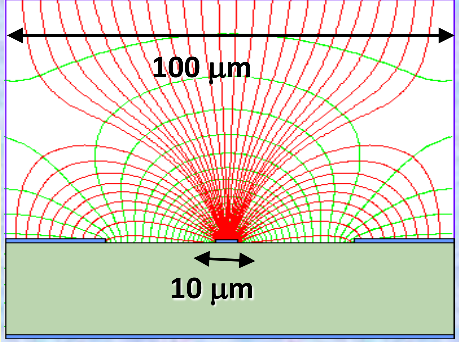
Higher Rate, enormous occupancy:
1D easily saturated → 2D → 3D

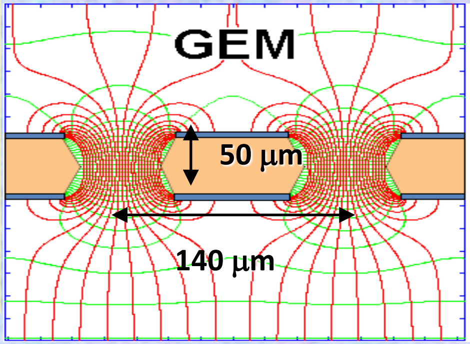
➤ **Silicon detectors:**
Strips →Pixels (2D)→ 3D-Si det.
& 3D electronics integration

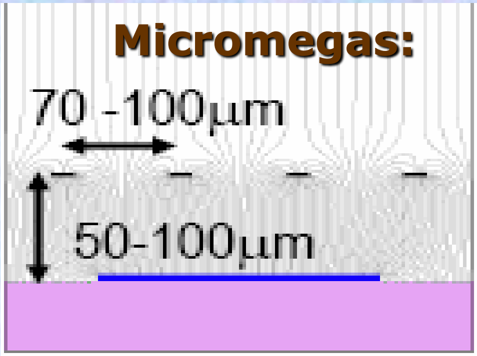
➤ **Gaseous detectors**
Wire Chamber → Wireless MPGD (2D)
→ InGrid/Timepix (3D)

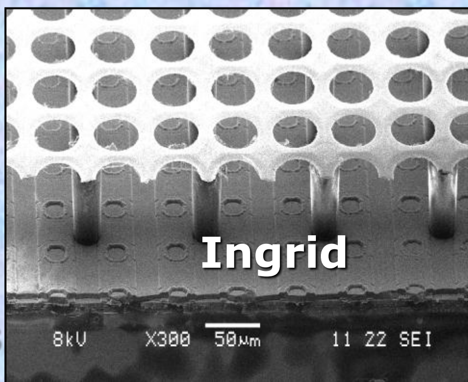


Advances in Micro-electronics & Etching Technology → Micro pattern Gaseous Detectors

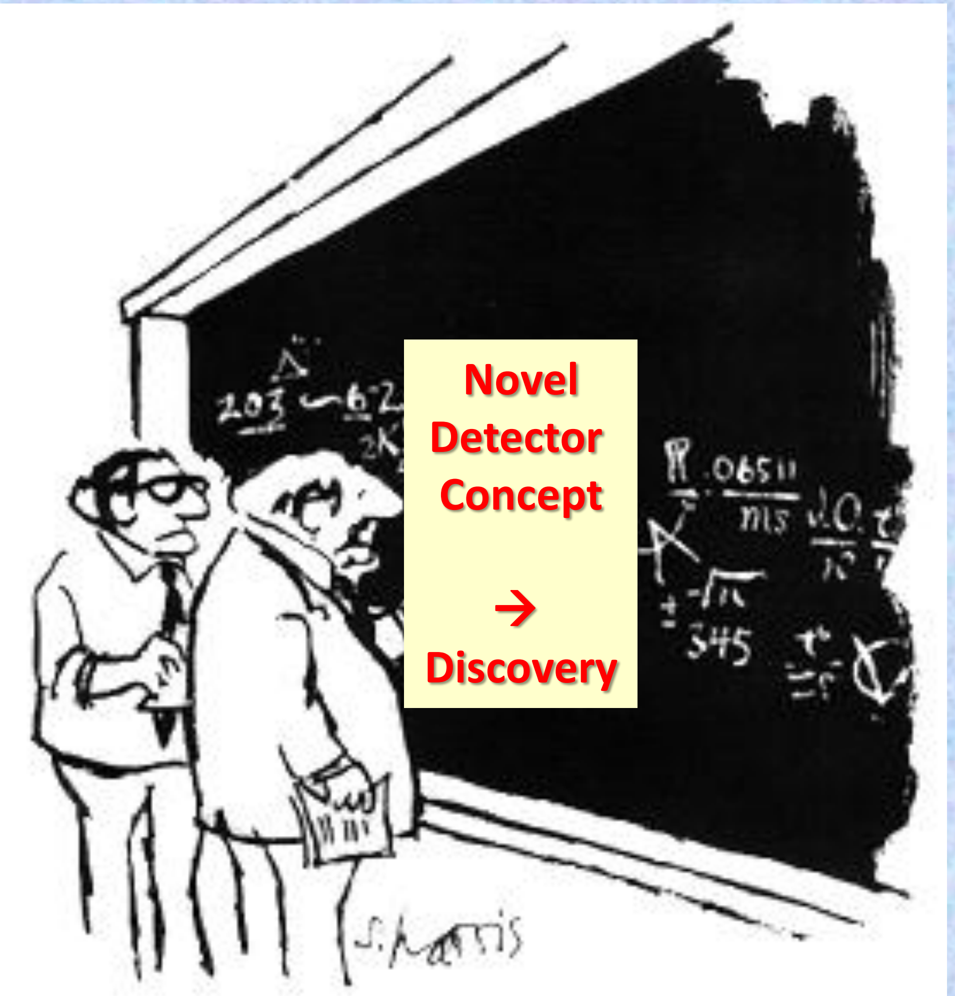








Thank You for listening and for Your questions



"I think you should be more explicit here in step two."