A gentle introduction

Detectors for Colliders

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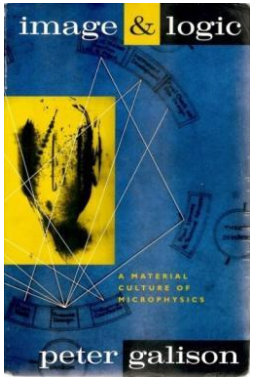
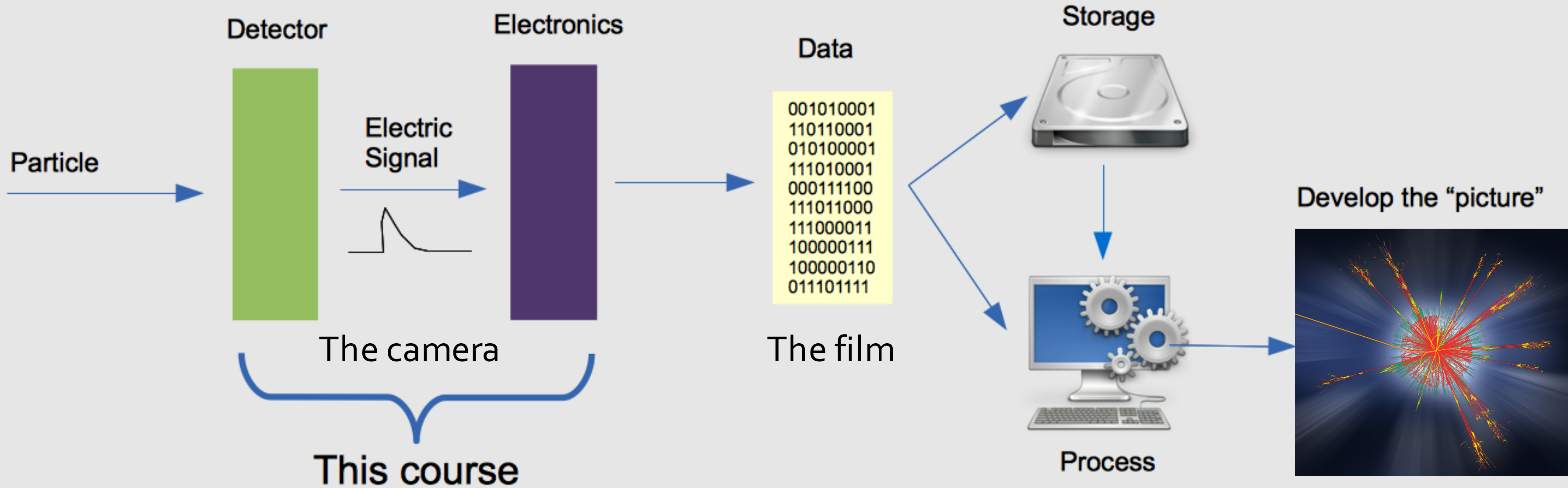
Outline

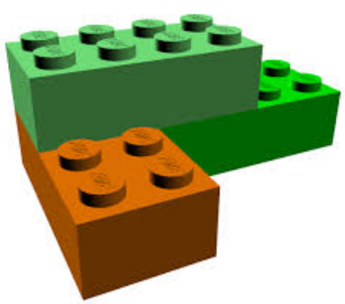
- Particle Detection
  - Interaction of particles with matter (a painless introduction)
- Particle Detectors: a historical overview
  - Image tradition
  - Logic tradition
  - Electronics image
- Tracking & Calorimetry
- A real example: the ATLAS detector at the LHC



A book worth reading if one likes instrumentation

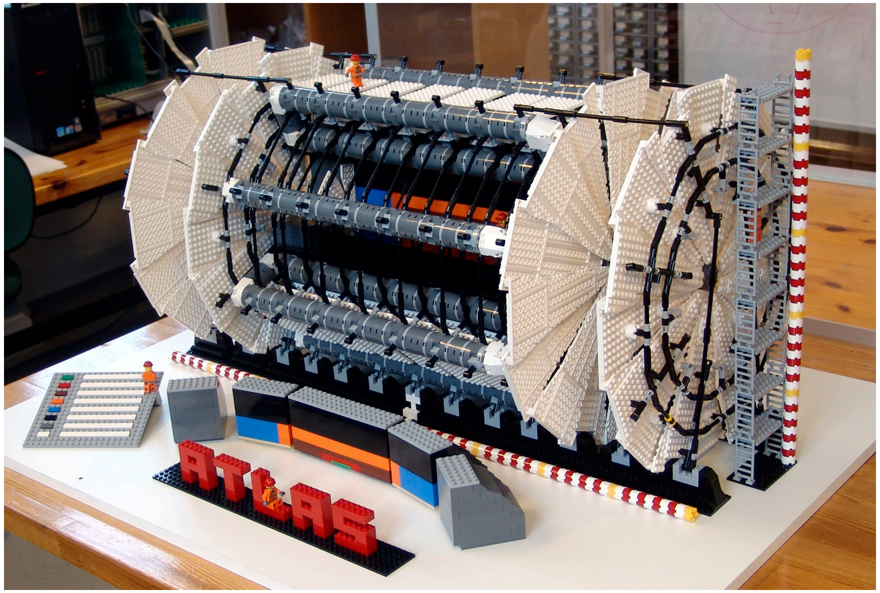
The Detection Process: from hits to histograms





From the small LEGO blocks to the whole system…

…the most tortuous path…

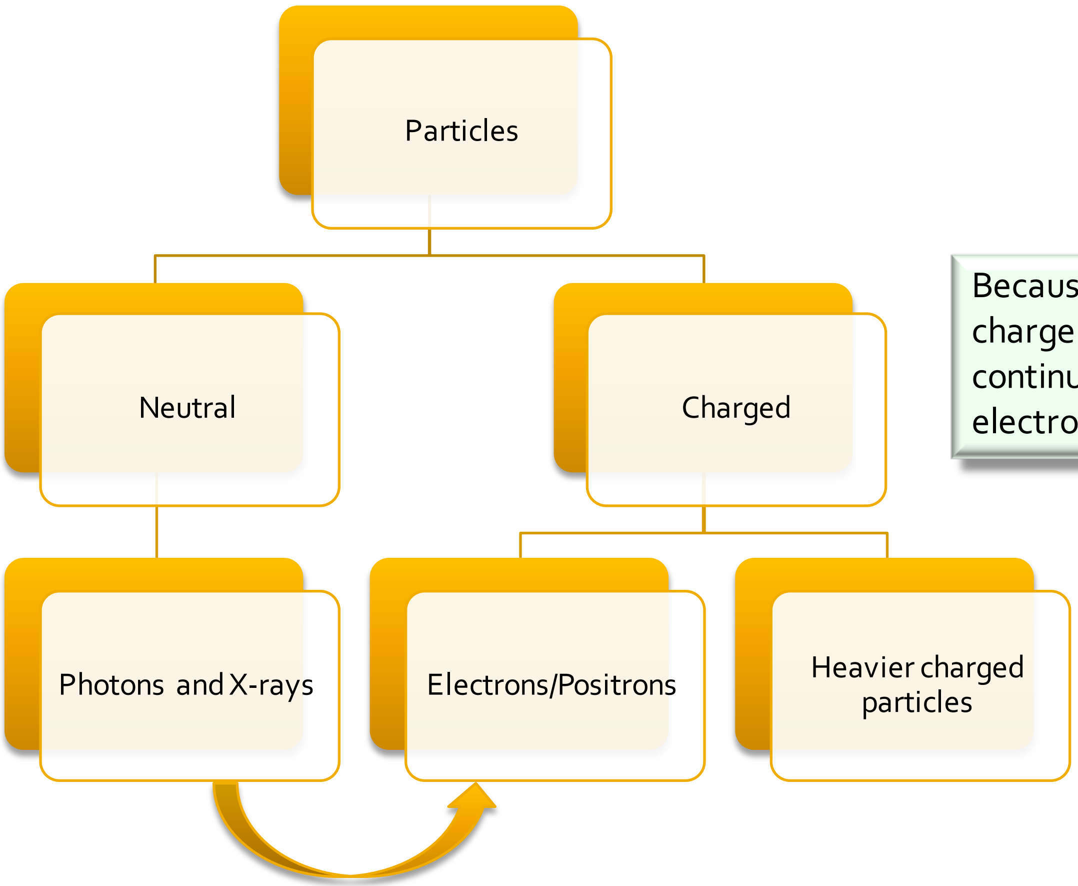


INTERACTION OF PARTICLES WITH MATTER

Interaction of particles with matter

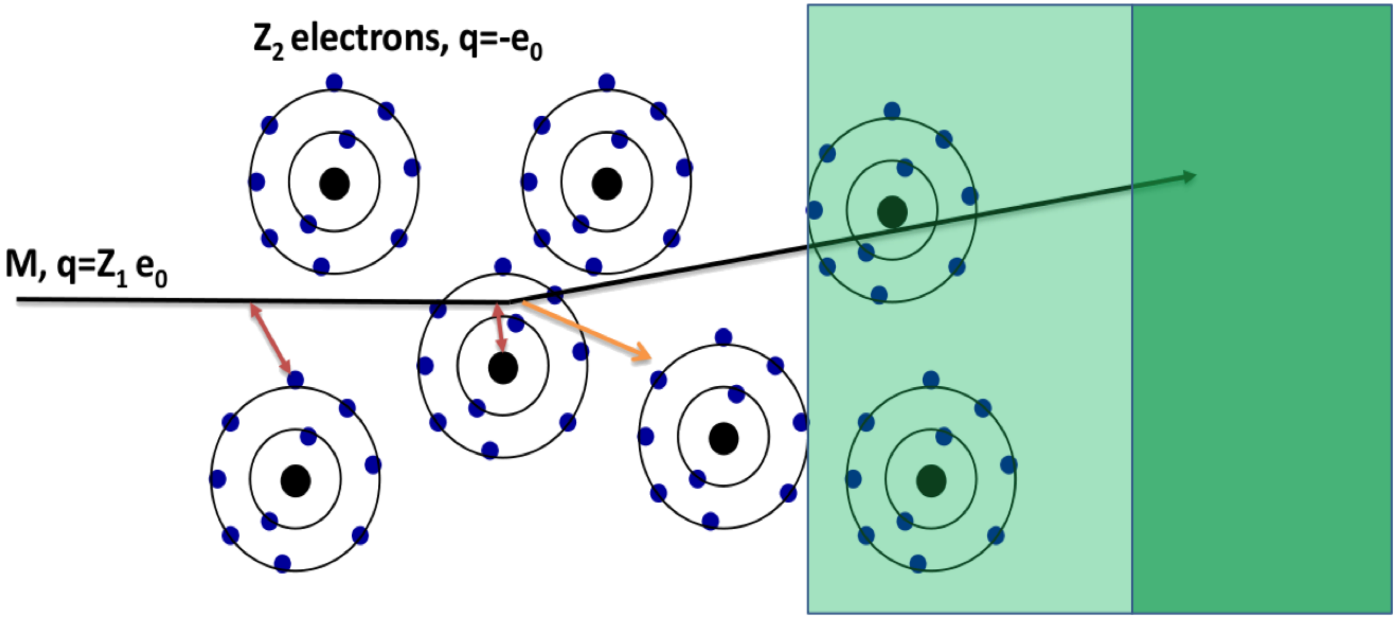
Interaction of particles with matter is the basis of all particle detection devices
Is also the basis of many "troubles" and "interferences" with our own measurements.

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



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are exited or ionized.

Interactions with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering. During this scattering a Bremsstrahlung photon can be emitted

If the particle's velocity is larger than the velocity of light in the medium, the resulting EM shock-wave manifests itself as Cerenkov radiation. When the particle crosses the boundary between two media, there is a probability (small) to produce an X ray photon called Transition radiation.

Charged particles loose there energy mainly by ionization of the atoms in the medium. We can "calculate" the average energy loss per unit length: -dE/dx

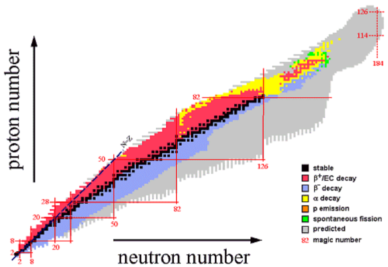
Charged particles: Bethe Block

$$-\frac{dE}{dx} = K\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2(\gamma\beta)^2T_{\max}}{I^2}\right)-\beta^2-\frac{\delta(\gamma\beta)}{2}-2\frac{C(I,\gamma\beta)}{Z}\right]$$

Particle Properties

Target Properties

Corrections

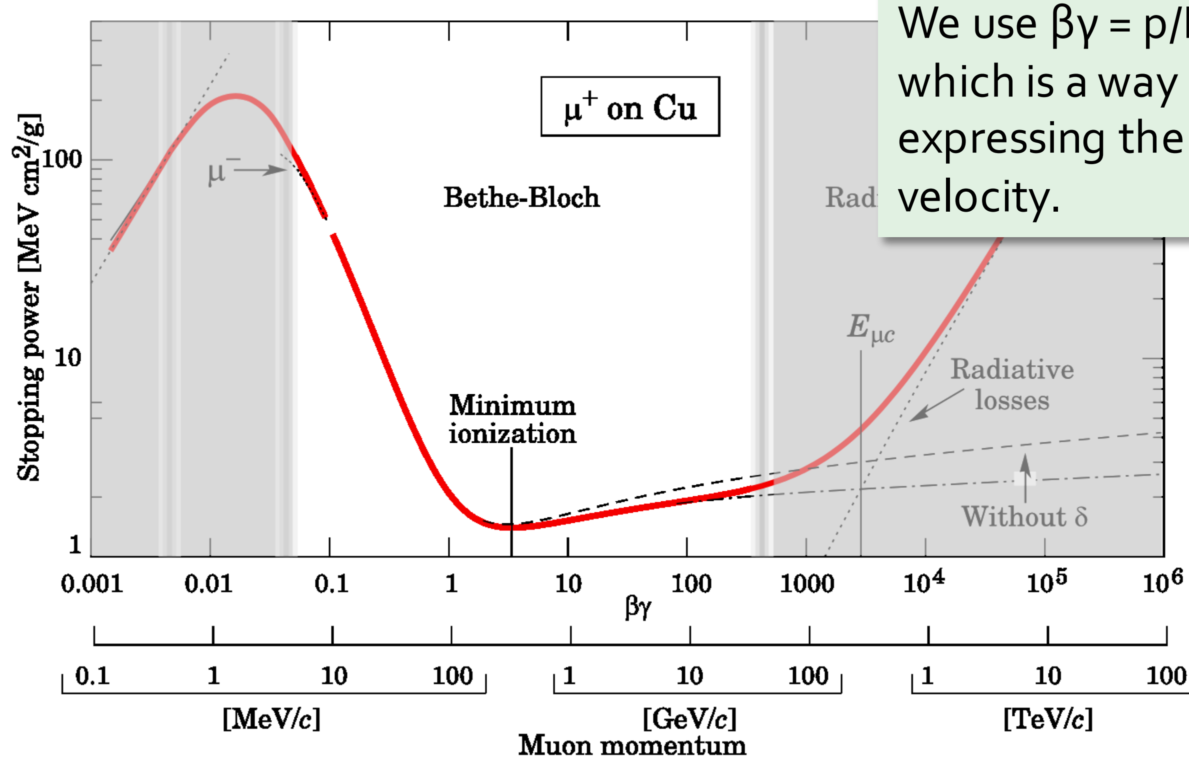


The stopping power

$$\frac{1}{\rho}\frac{dE}{dx}$$

Is independent of material since Z/A is almost constant.

dE/dx depends on density of target



We use βγ = p/Mc which is a way of expressing the velocity.

Charged particles: Bethe Block

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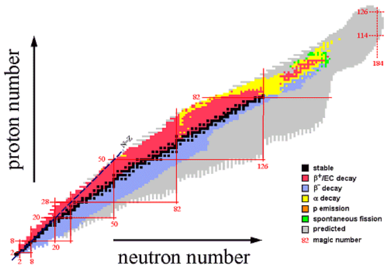

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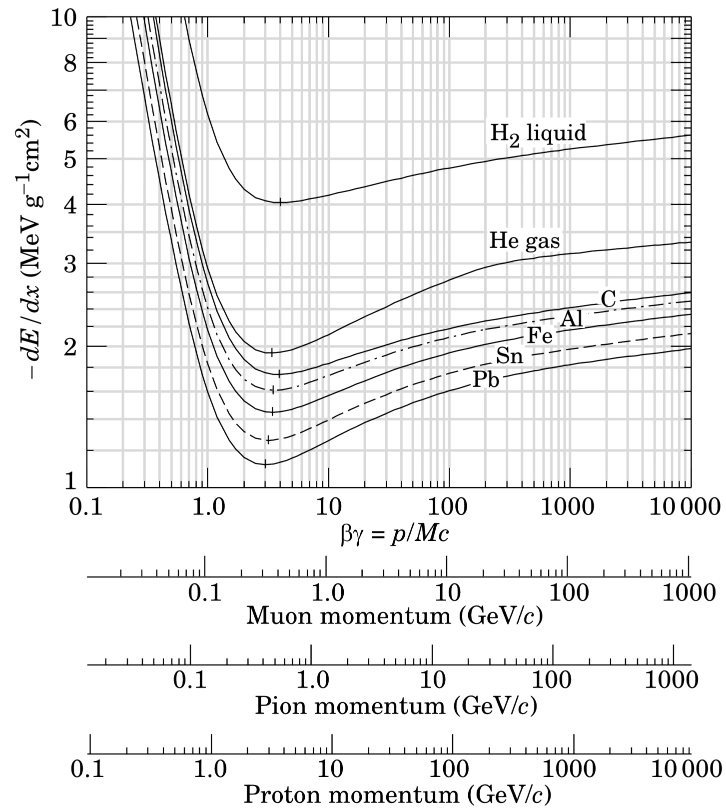

We use $\beta\gamma = p/Mc$ which is a way of expressing the velocity.

Charged particles

Particle Properties

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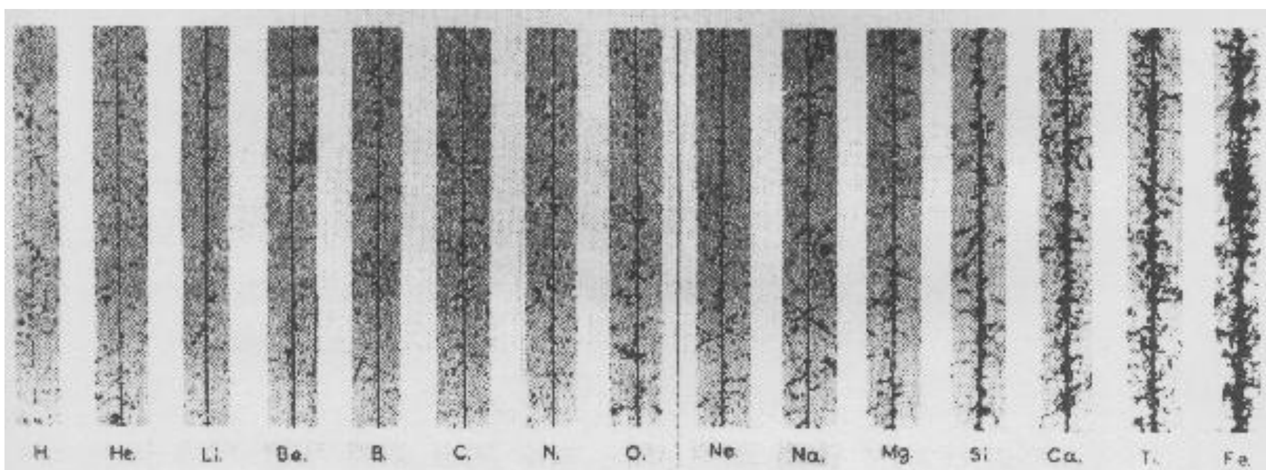
Target Properties

Corrections

Proportional to z^2 of the incoming particle.

Protons (z=1) lose less than α particles (z=2) and much less than Carbon ions (z=6)



Nuclear emulsions: films were exposed to cosmic rays at high altitude by using balloons

Charged particles

Particle Properties

$$-\frac{dE}{dx} = K\rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2(\gamma\beta)^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\gamma\beta)}{2} - 2\frac{C(I,\gamma\beta)}{Z}\right]$$

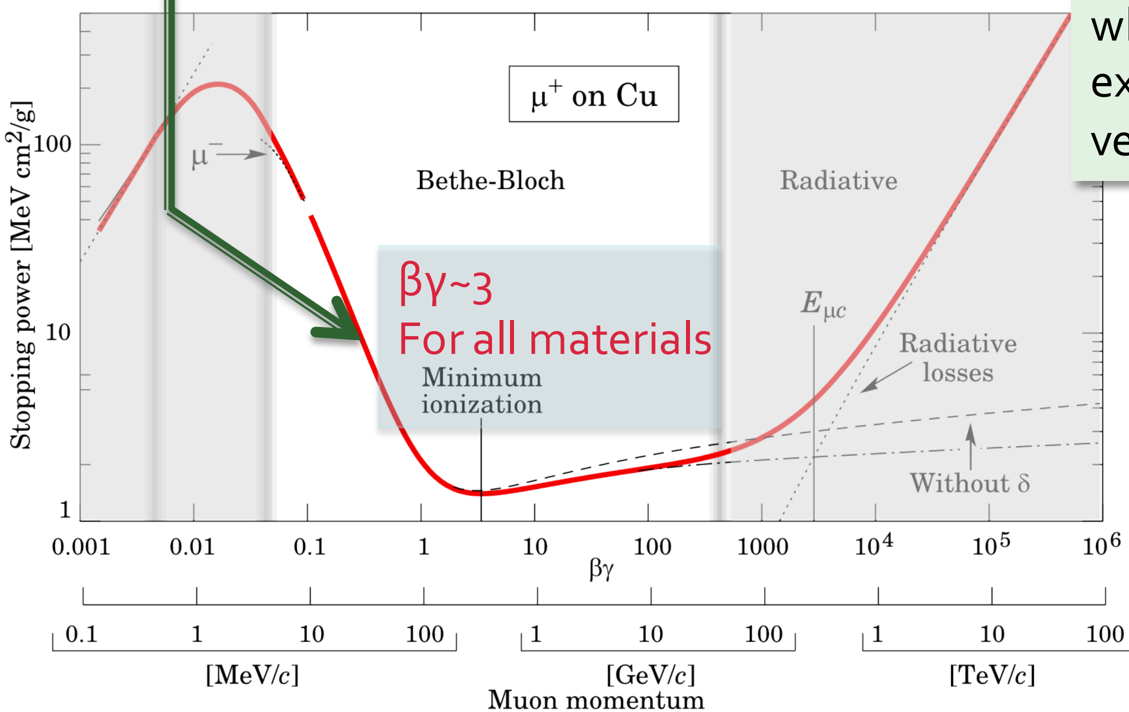
Target Properties

Corrections

We use βγ = p/Mc which is a way of expressing the velocity.

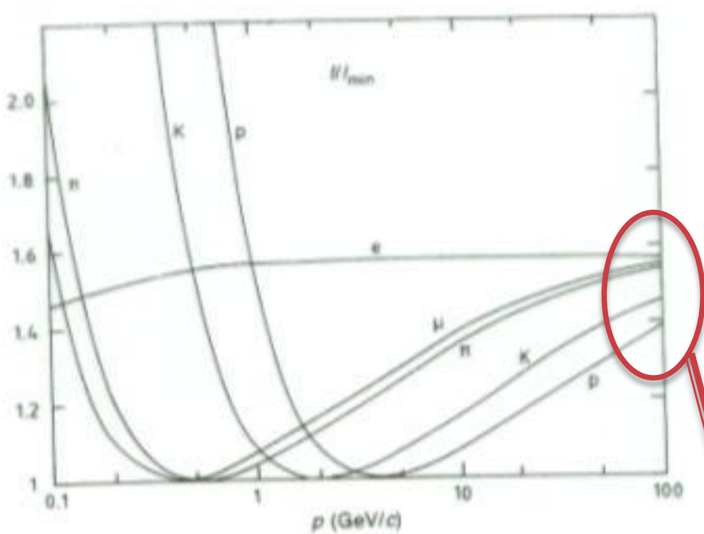
At low velocities,

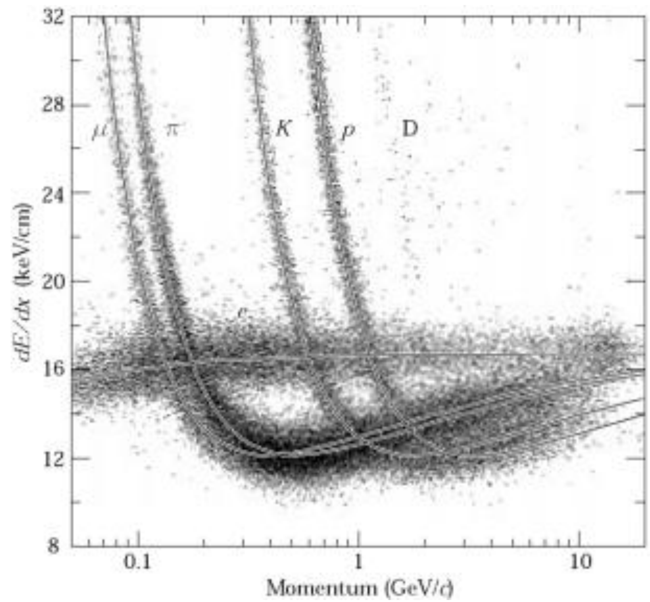
1/β² dominates. Then at βγ=3 we reach the minimum: MIP



Energy deposition

When expressing dE/dx as a function of the particle momentum (p=mv, so we change the particle velocity, v, by p/m) we are adding a dependence with the mass that can allow us to differentiate among different particles at low momentum

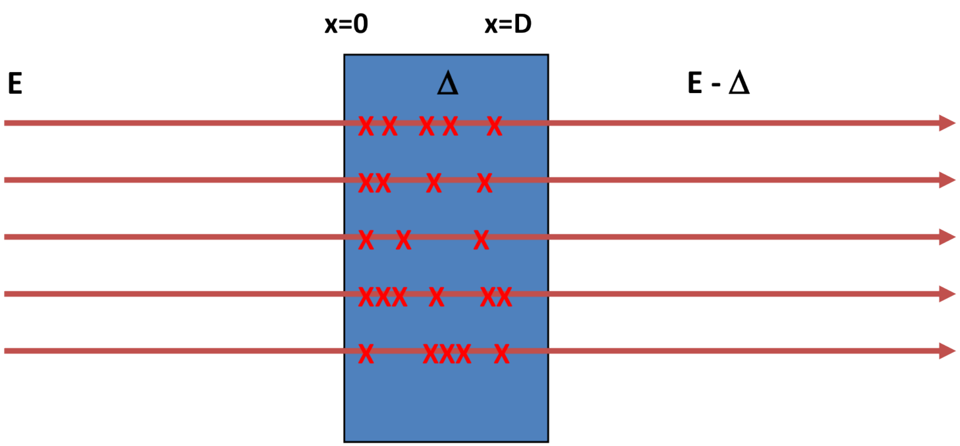


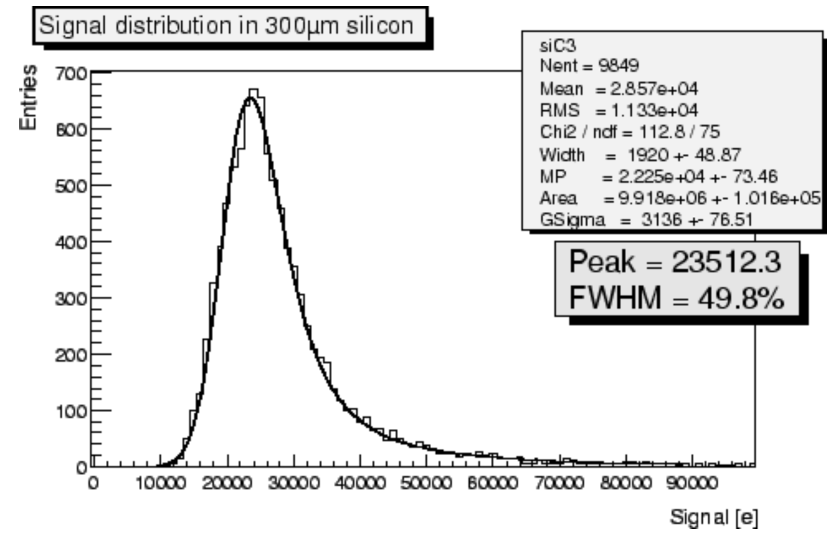


At high momentum, the energy deposition is "almost" the same for all particles in the same material

Average Energy deposition

- Interactions are of statistical nature
- For a given thickness we obtain an energy probability distribution rather than a fixed energy
- The distribution depends on the thickness:
  - Thin: Landau
  - Think: Gauss (Law of Large Numbers…)



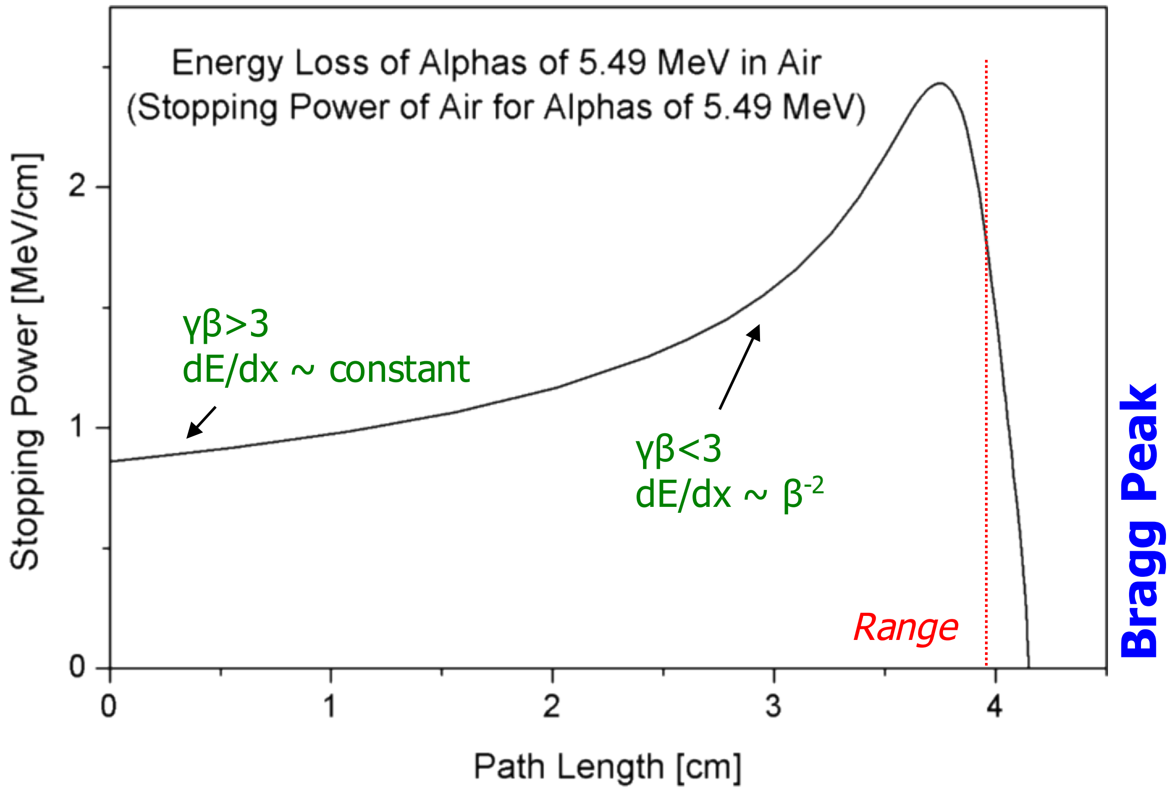


The Bragg curve

Plot of the stopping power along the track of a particle: **The Bragg Curve**

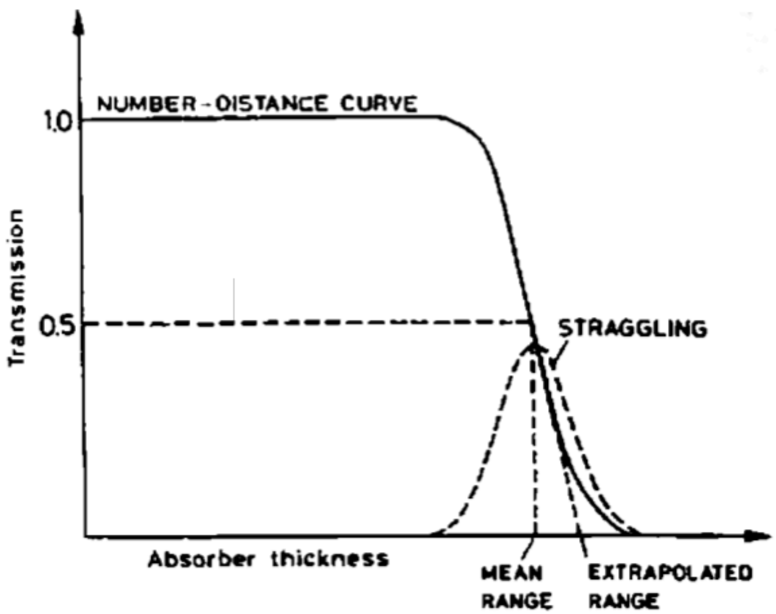
Most of the energy is lost at the end of the track: **The Bragg Peak**

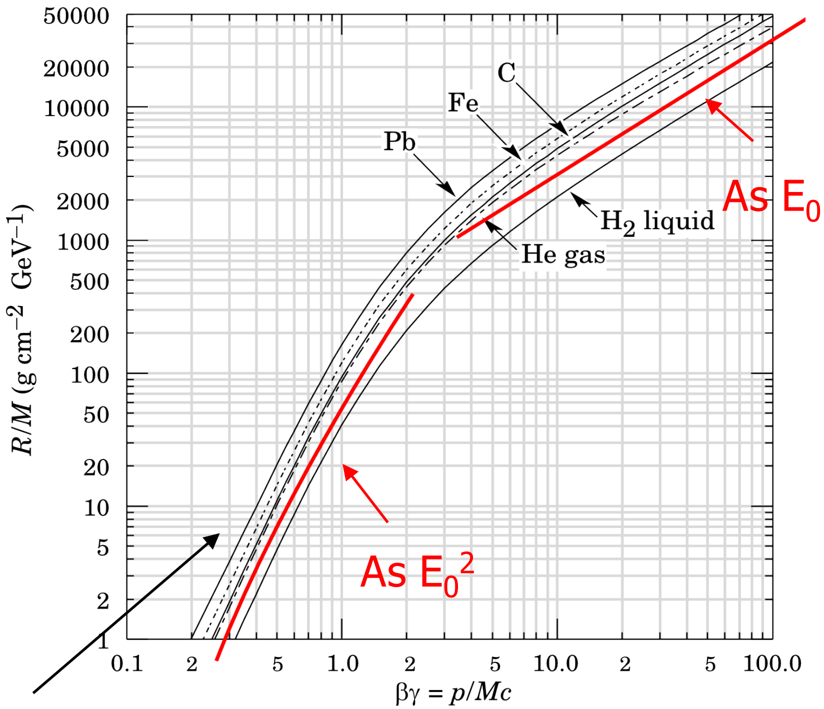
Track length defines the range of the particle



Range of Particles

For a beam of particles, the range is the distance at which half of them have lost all their energy. It depends on the particle, its "initial" kinetic energy (E_o) and the material





We compute it from the average energy loss:

$$R(E_0) = \int_{E_0}^{0} \frac{-1}{dE/dx} dE$$

$$\frac{\rho}{Mc^2} R(\beta_0\gamma_0) = \frac{1}{z^2}\frac{A}{Z} f(\beta_0\gamma_0)$$

Independent of material

R/M ~ E_o^2 before the MIP and
R/M ~ E_o after MIP

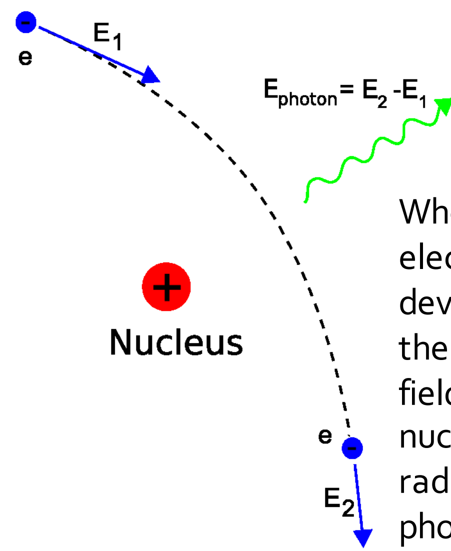
Electrons and Positrons: Radiation

In addition to ionization, electrons and positrons may radiate due to their small mass.

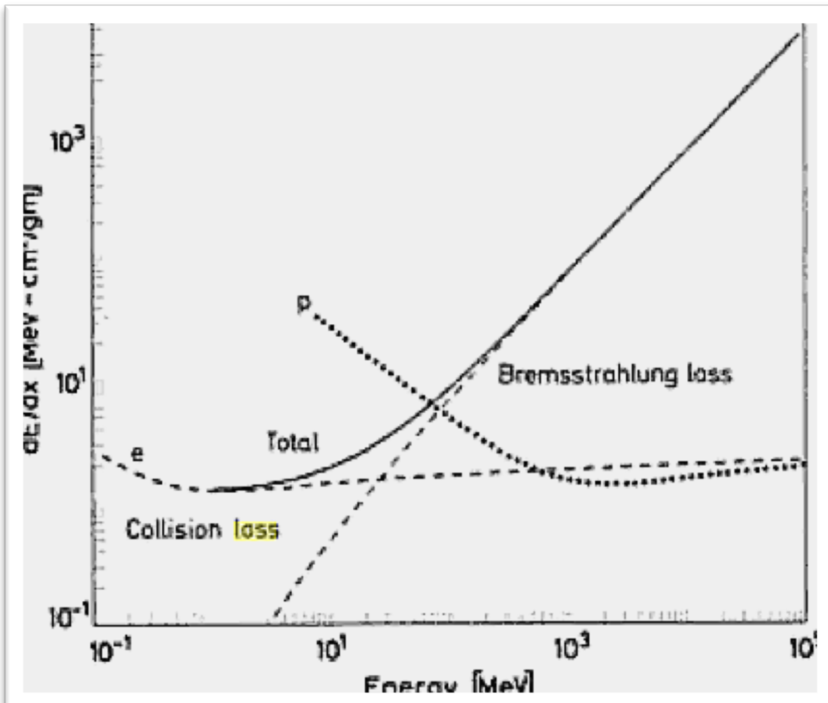
Cross section for radiation (Bremsstrahlung) proportional to

$$\frac{z^4 Z^2}{M^2 E_{photon}}$$

Next heavier particle is the Muon: prob. is 40000 times smaller than for electrons



When the electron is deviated by the electric field of the nucleus, it radiates a photon



Radiation length (X_o) : distance over which the electron energy is reduced to a factor 1/*e* of its energy due to Bremsstrahlung.

Radiation Length

The **radiation length (X_0)** is the characteristic length that describes the energy decay of a beam of electrons:

$$E = E_0 \, e^{-\frac{x}{X_0}} \qquad X_0 \approx 180 \frac{A}{Z^2} \ g/cm^2$$

Why do we like it ?

Radiation loss is approx. independent of material when thickness expressed in terms of Xo:

$$-\frac{dE}{dt} \approx E_0$$

Where t is distance in radiation length and E_0 the initial energy.

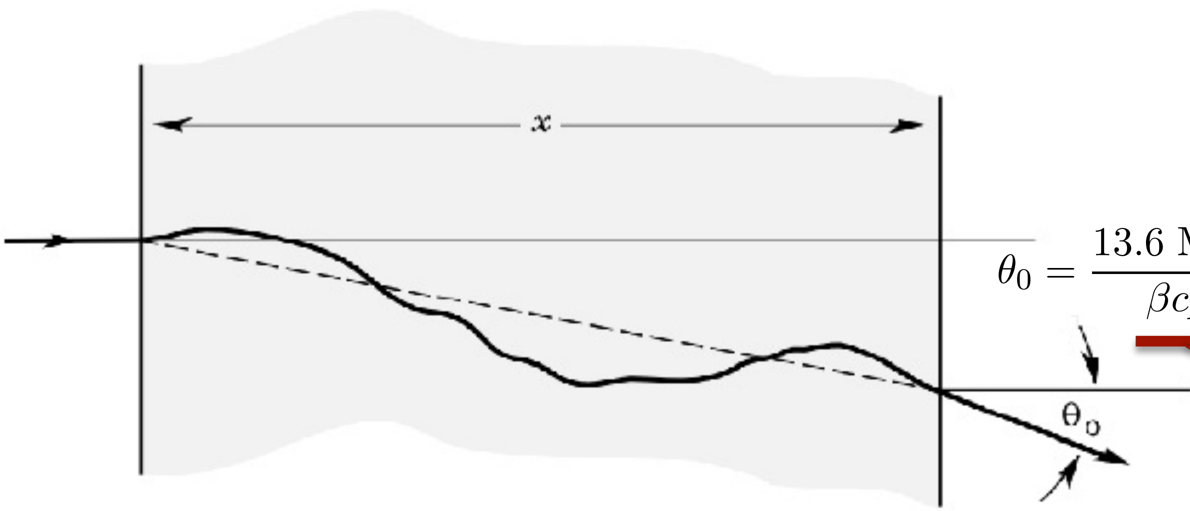
Material	g/cm²	cm
Air	36.20	30050.00
Water	36.08	36.10
Pb	6.37	0.56
Fe	13.84	1.76
Si	21.82	9.36
NaI	9.49	2.59

Multiple Scattering

Some times we want to detect the point at which a particle traverses a detector.

If we want high precision, about micrometers, we have to care about the particle path inside the sensor.

In addition to inelastic collisions with the atomic electrons, particles passing through matter suffer **repeated elastic Coulomb scattering from nuclei** although with a smaller probability. The energy transfer is small due to mass difference, but the trajectory is changed



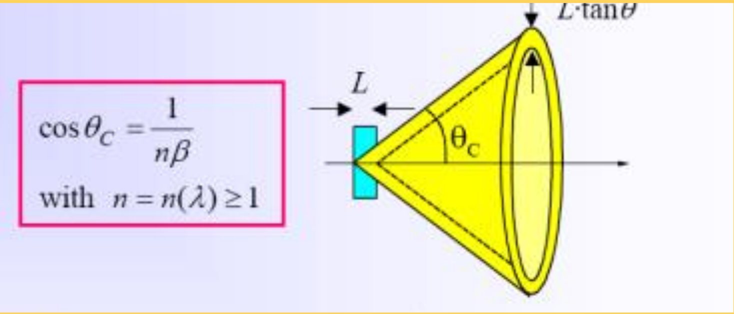
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$

Thickness: in radiation length.

Momentum and speed.

Cerenkov Radiation

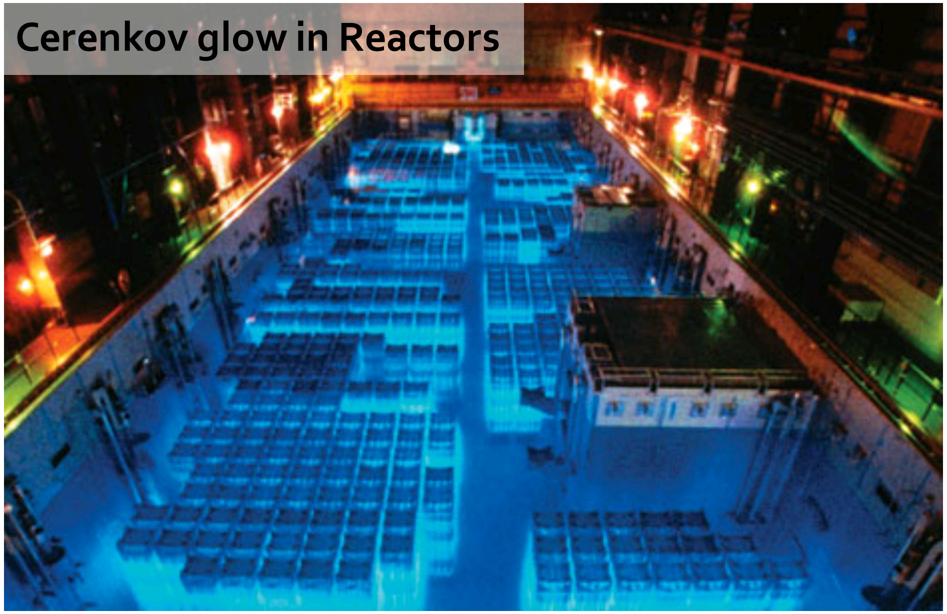
By mid 1930 the bluish glow that accompanied the passage of radioactive particles through liquids was analysed and largely explained (Cerenkov Radiation).



Cerenkov 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.

We can detect the light with a photomultiplier



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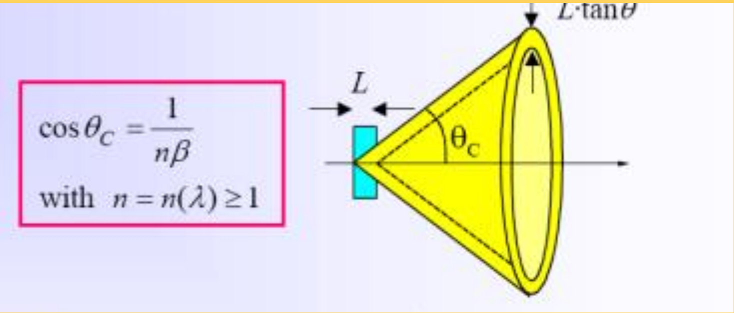
Godzilla´s atomic breath



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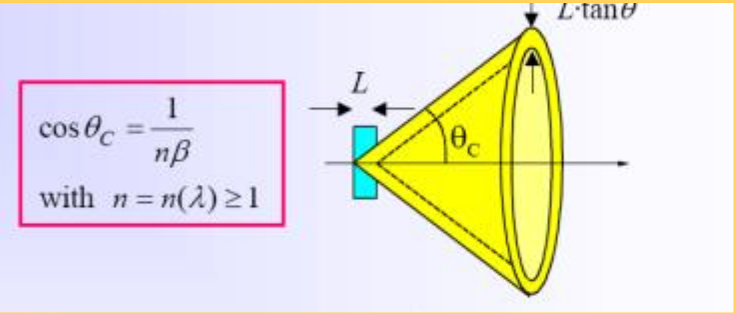
Dr. Manhattan´s glow (Watchmen)



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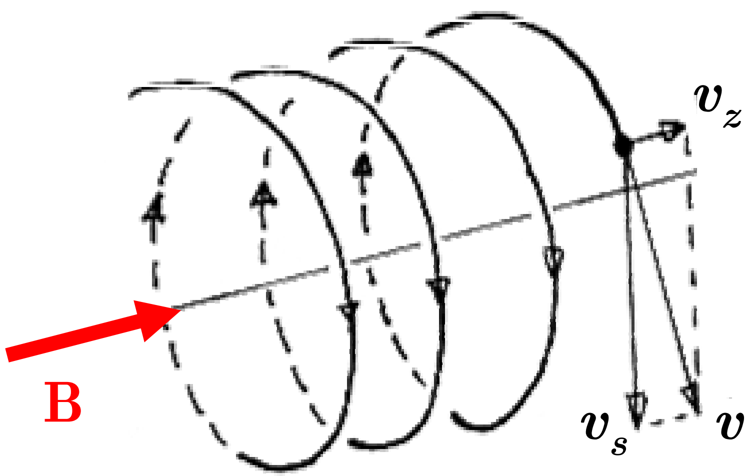
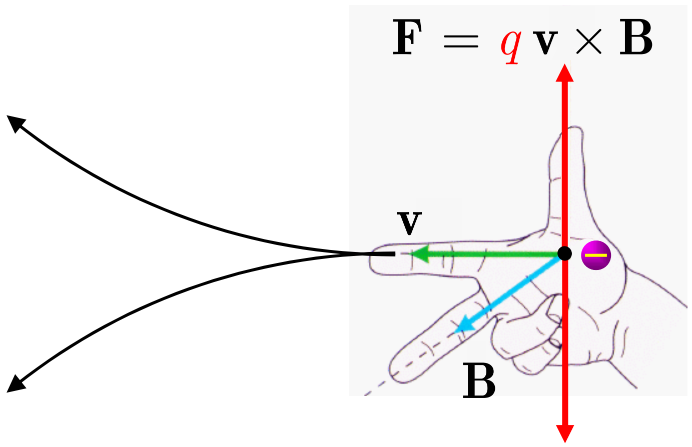
Magnetic Field

Motion of a charged particle in a magnetic field is determined by Lorentz Force

$$\frac{d\boldsymbol{p}}{dt} = q\,\boldsymbol{v} \times \boldsymbol{B} \;\rightarrow\; \frac{d^2\boldsymbol{r}}{ds^2} = \frac{q}{p}\,\frac{d\boldsymbol{r}}{ds} \times \boldsymbol{B}$$

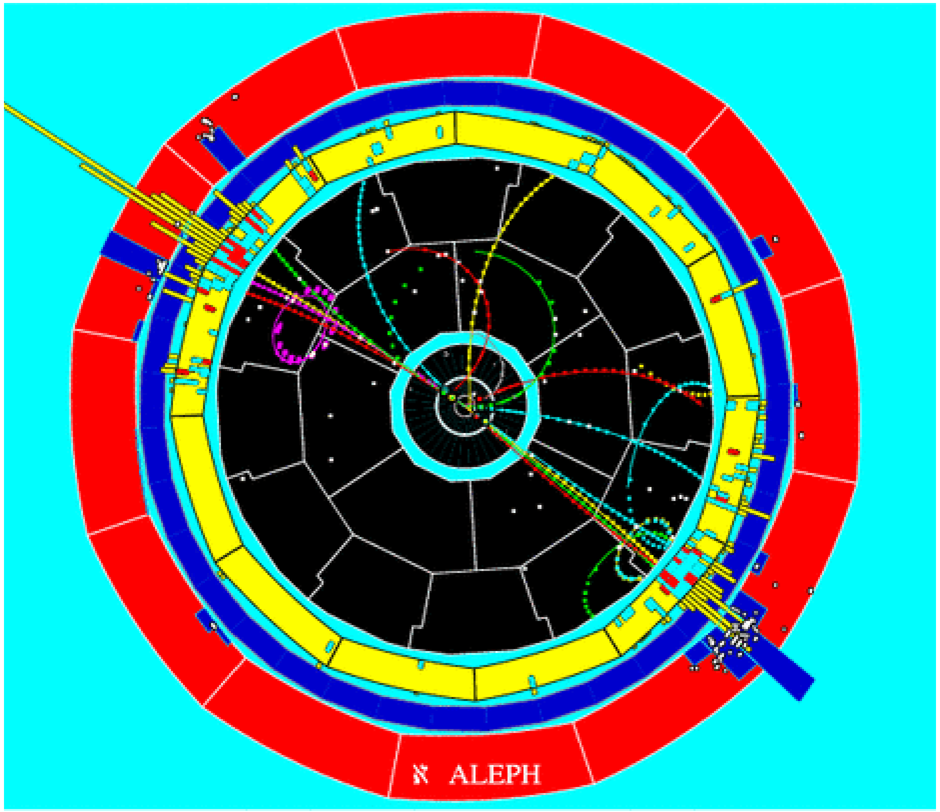
The **trajectory is an helix in case of a uniform field** with the particle trajectory deflecting in the plane transverse to the field.
The radius of curvature depends on the transverse momentum: $R \sim p_T/B$
We can "separate" particles by charge and momentum ("spectrometer")

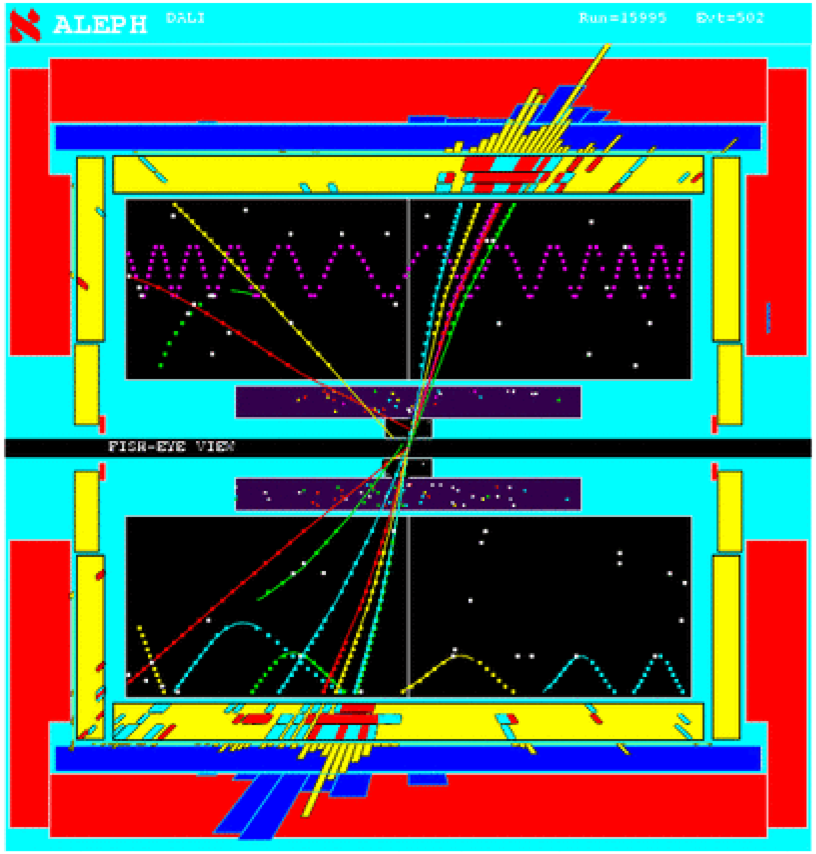




Magnetic Field

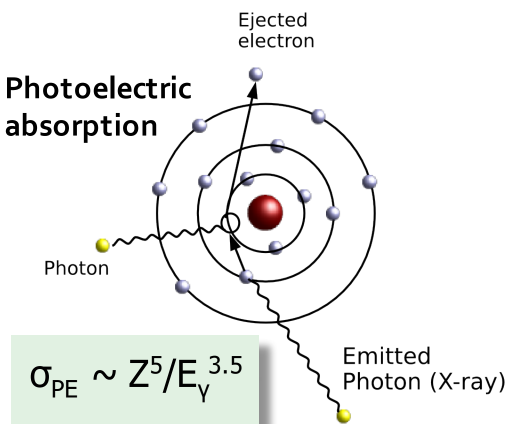
We do see the helix in our detectors



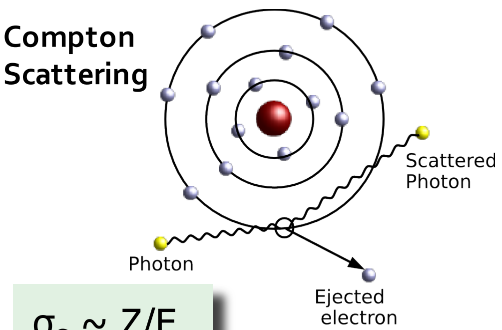


Photon interactions

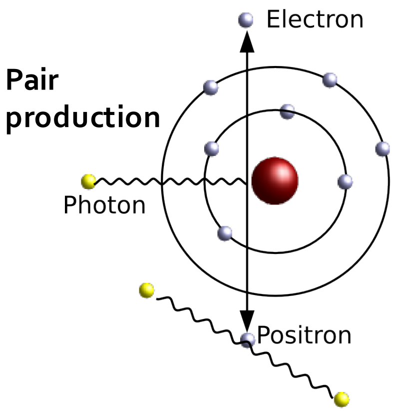
Photons interact very differently.
Contrary to charged particles that deposit energy continuously due to ionization, photons usually suffer one-off interactions producing charged particles

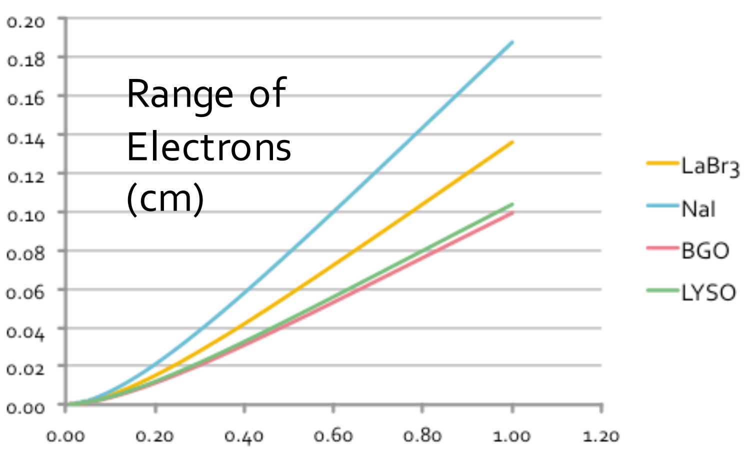


$\sigma_{PE} \sim Z^5/E_\gamma^{3.5}$



$\sigma_C \sim Z/E_\gamma$

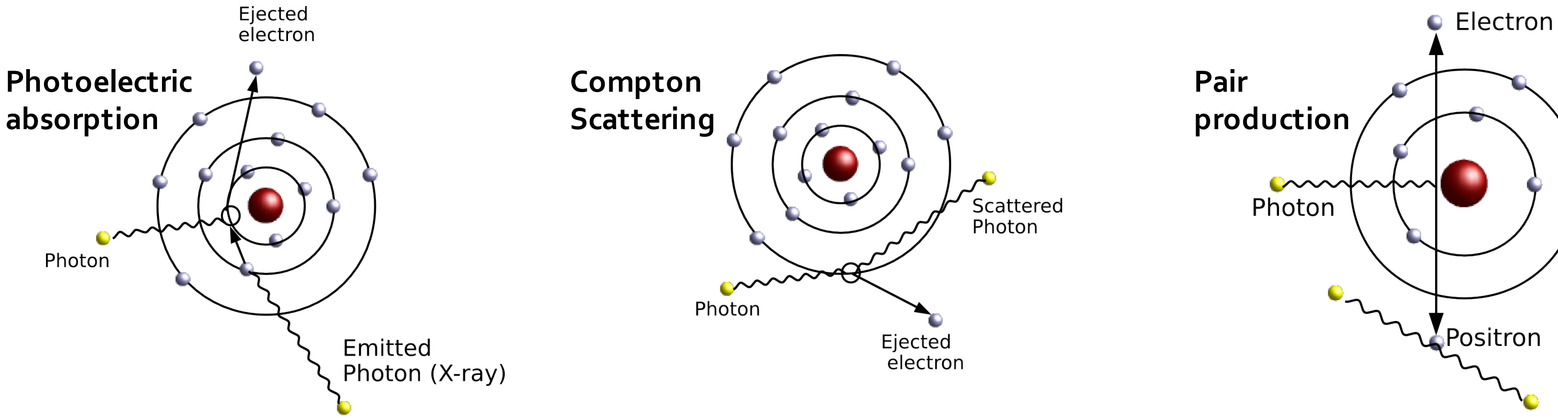


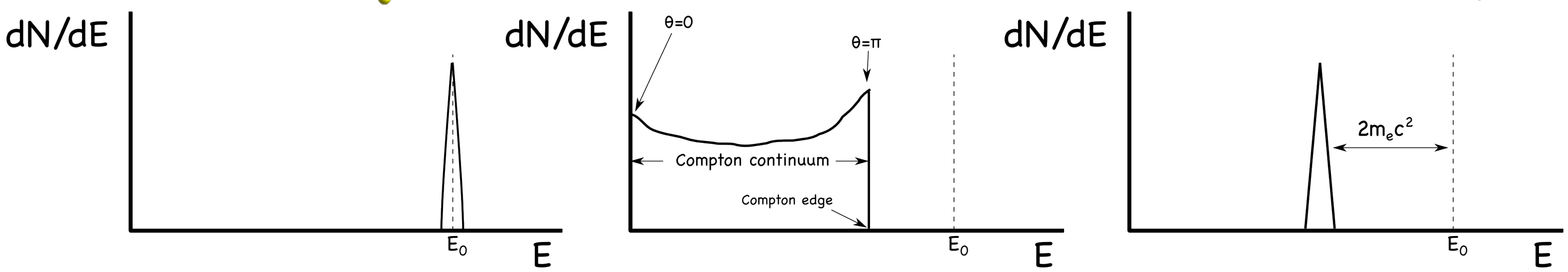


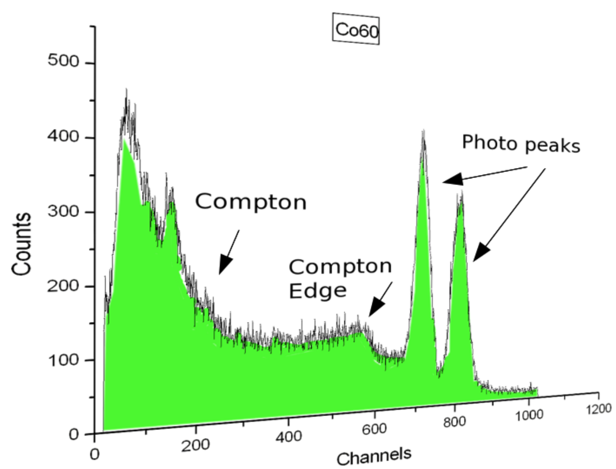
Secondary particles produced are mainly electrons with sub-millimetric range.

They are absorbed in the detector.

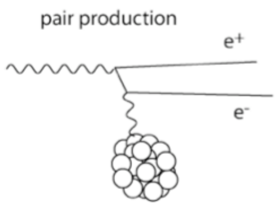
Photon Interactions







Radiation Length (revisited)

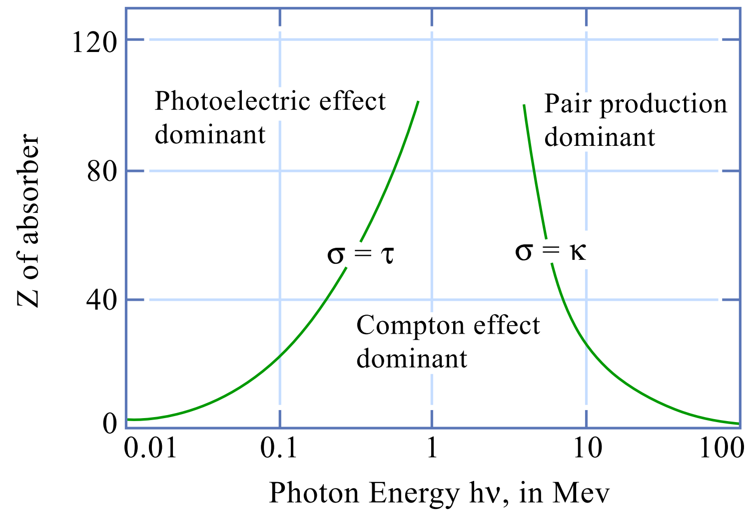


When speaking about photon interactions….

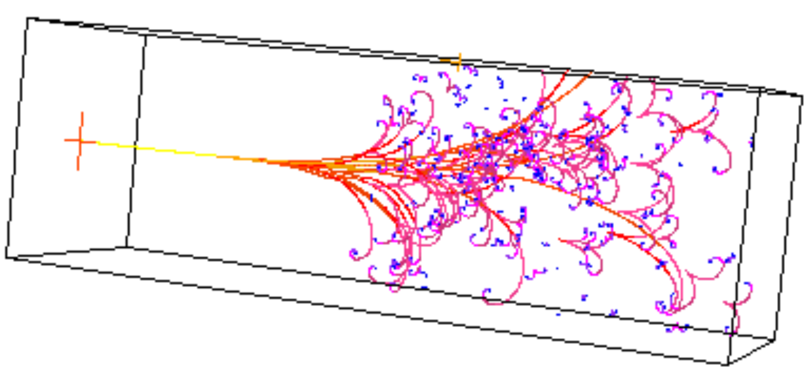
High energy photons lose energy by pair production. Mean free path for pair production

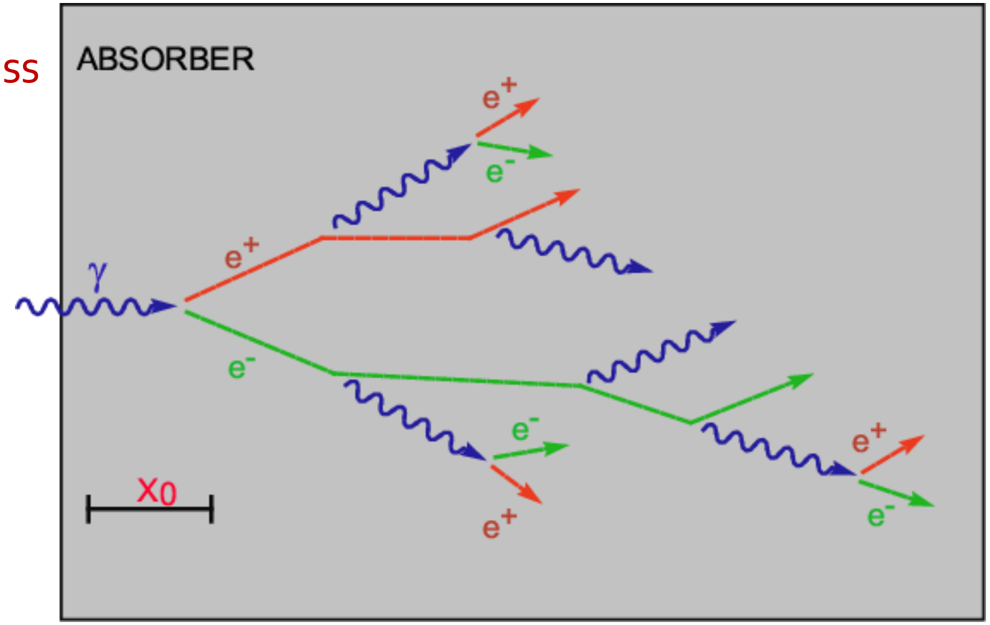
$$\lambda = \frac{9}{7} X_0$$

For electrons (remember), $\lambda = X_0$.



Then we have high energy electrons that generate high energy photons and the process repeats: **an electromagnetic shower**.





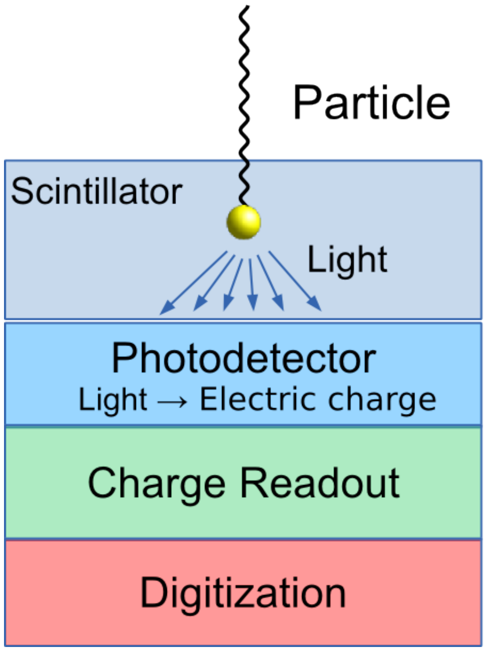
DETECTOR INTERNALS

A particle detector

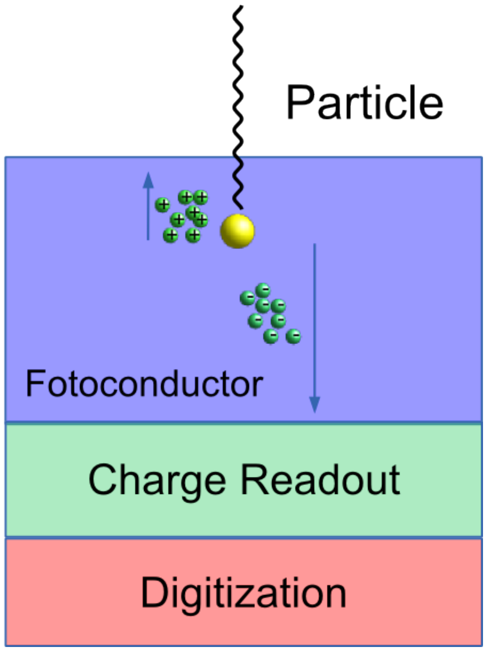
- Particles deposit energy in the detector material.
- The interactions are mainly with atomic electrons: ionization
  - If the particle does not ionize, produces secondaries that do.
- Our goal is
  - Convert the energy deposited in an electrical signal that we can play with
  - There is some relationship, hopefully linear, between energy and signal properties.

Indirect detection

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



Direct detection



The ionization creates mobile charges that we can detect

The signal production

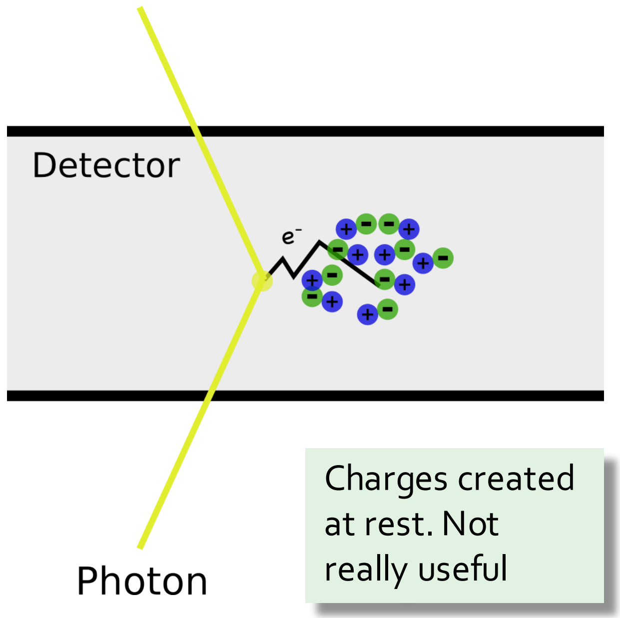
- The energy deposited by the particle can produce
  - Excitation of individual atoms to produce electron-ion pairs in gas detectors, electron-hole pairs in semiconductor detectors
  - Excitation of optical states in scintillators
  - ...
- The energy required to produce a pair of "charge-carriers", the ***excitation energy (ε), depends on the detector material***:
  - Ionization in gases: 30 eV
  - Semiconductor detectors: 1-5 eV
  - Scintillators: 100-1000 eV
- The average number of "signal quanta" will be

$$N = \frac{E}{\epsilon}$$

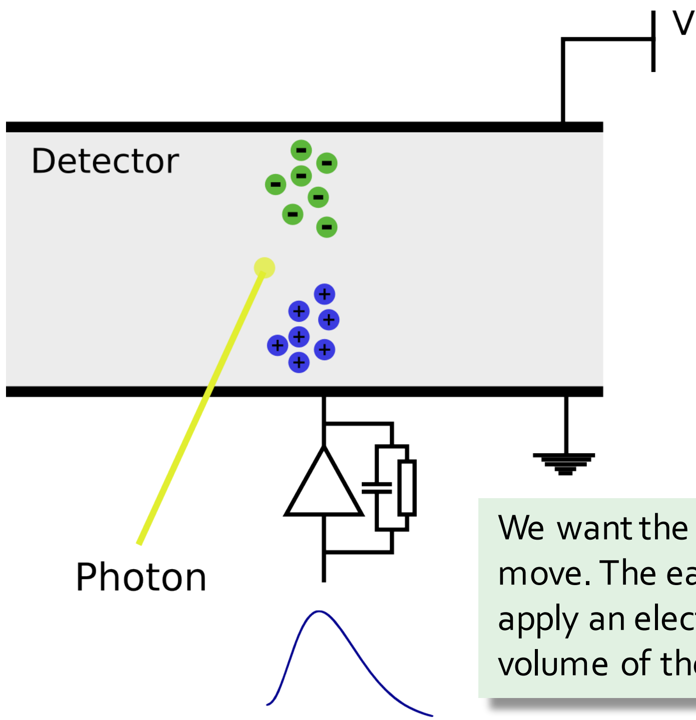
- This is a statistical quantity (Poisson), so the intrinsic energy resolution can be written as

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \underbrace{\frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}}_{Poisson} \propto \frac{1}{\sqrt{E}}$$

- Ionization creates charges in the detector volume.
  - Electron-ions in gaseous detectors
  - Electron-hole pairs in semiconductor detectors
- We apply an electric field to move them and "induce" an electric current.



Charges created at rest. Not really useful



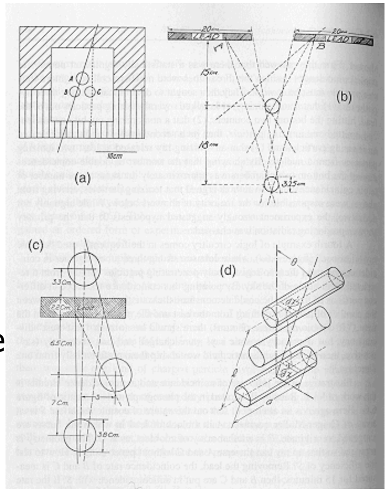
We want the charges to move. The easiest is to apply an electric field in the volume of the detector.

DETECTORS

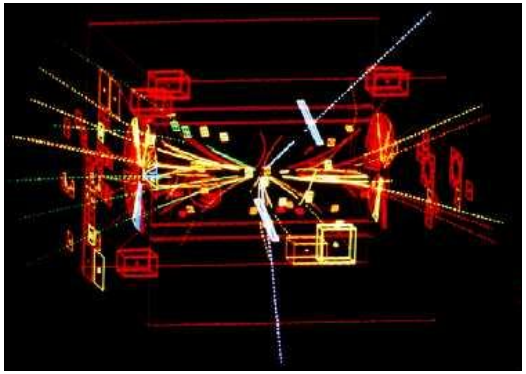
Detectors

- Image tradition
  Representation of natural processes in all their fullness and complexity
  - Cloud chamber, Emulsion, Bubble Chamber
- Logic tradition
  Uses electronic counters coupled to electronic logic circuits. Counting (rather than picturing) machines that aggregate masses of data to make statistical arguments….
  - Scintillator, Geiger Counter, Tip Counter, Spark Counter
- Electronics image:
  The new instruments meld together the data-sorting capability of the logic tradition with the detail and inclusiveness of the image tradition
  - Wire chambers, Time Projection Chambers, semiconductor detectors
  - …

Bubble chamber photograph

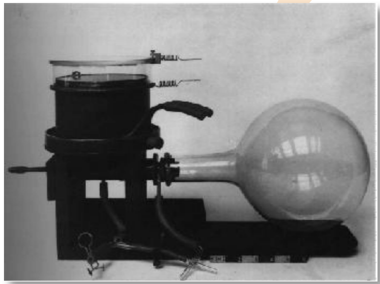


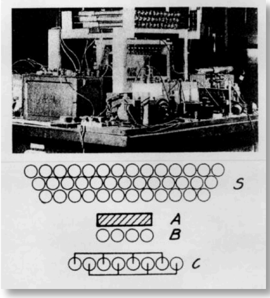
Early coincidence counting experiment



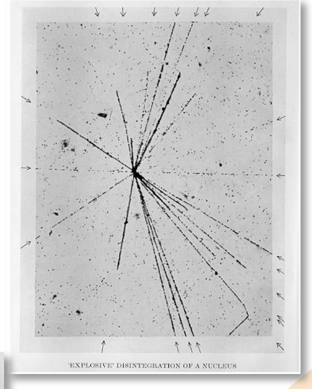
Z discovery at UA1 CERN in 1983

Particle detector developments



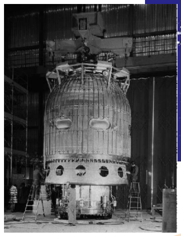


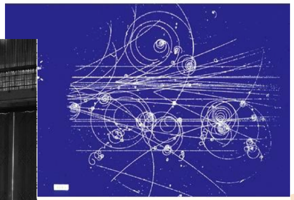
Cloud chambers/Geiger Müller



Films/Emulsions

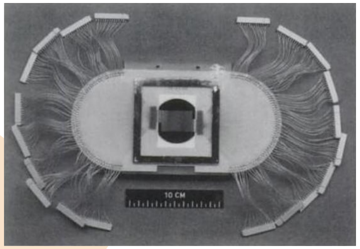
Scintillator counter

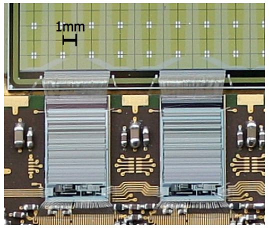




Bubble/ spark/ wire Chambe

Semiconductor detectors



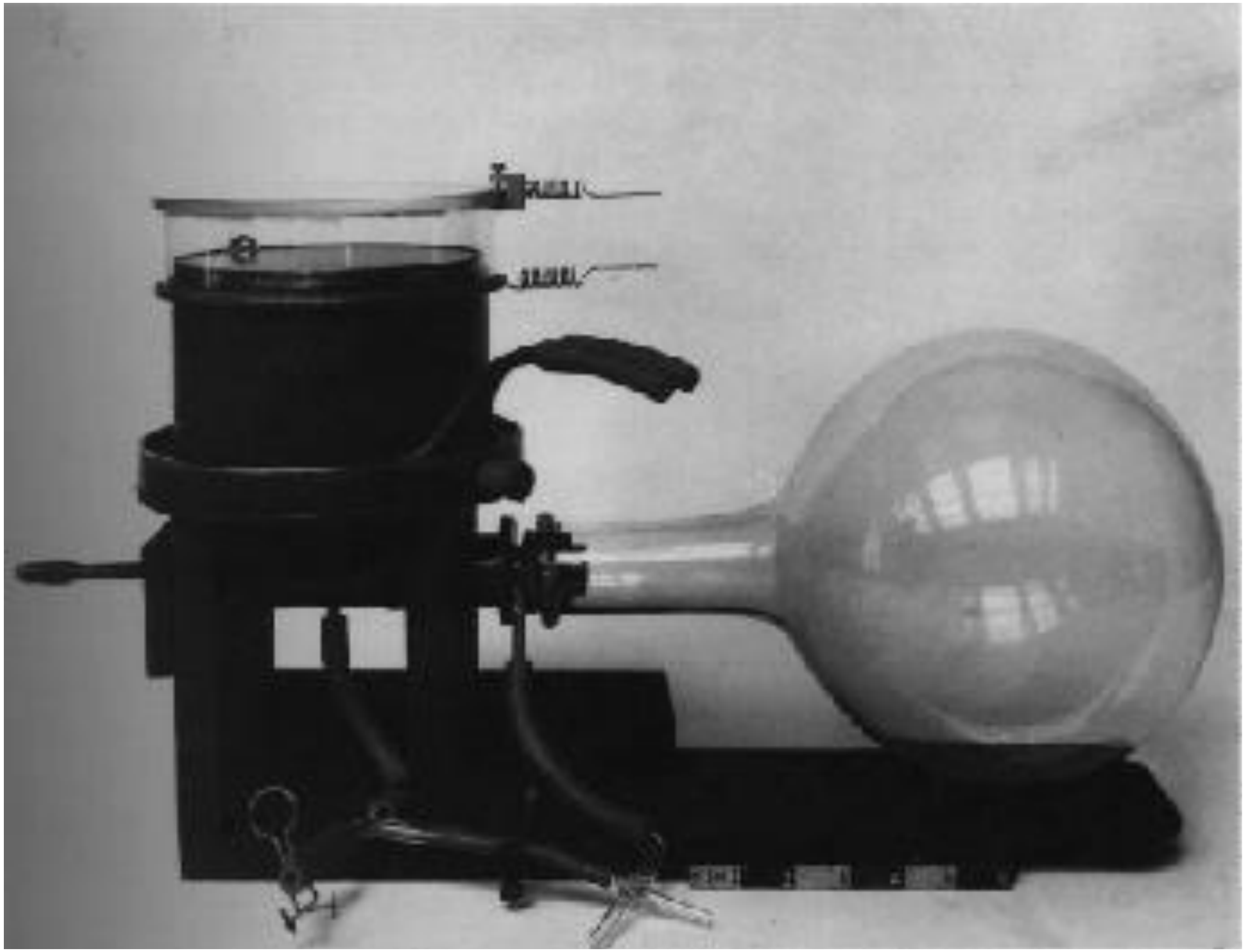


Second World War. Fantastic boost to electronics systems

Encapsulation allows to produce more compact and complex systems.

IMAGES

Cloud Chamber

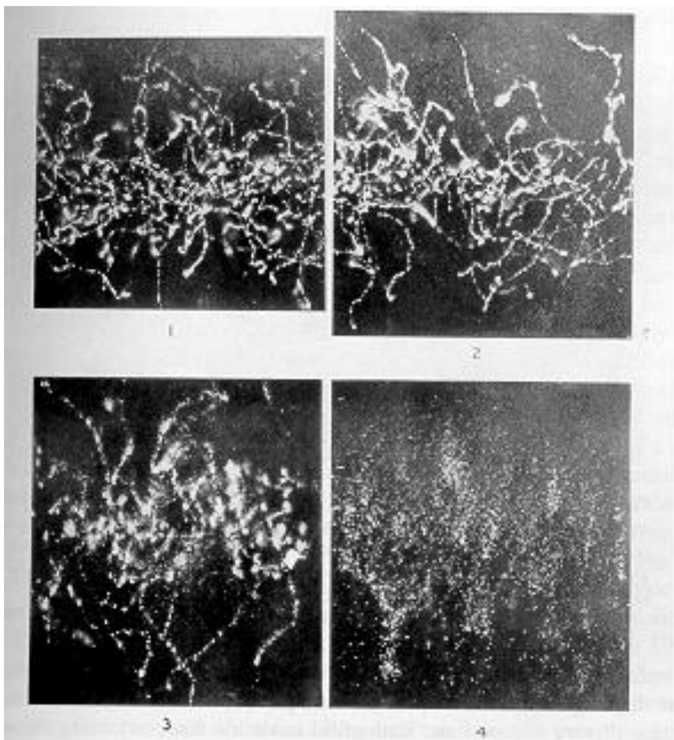


Wilson Cloud chamber 1911

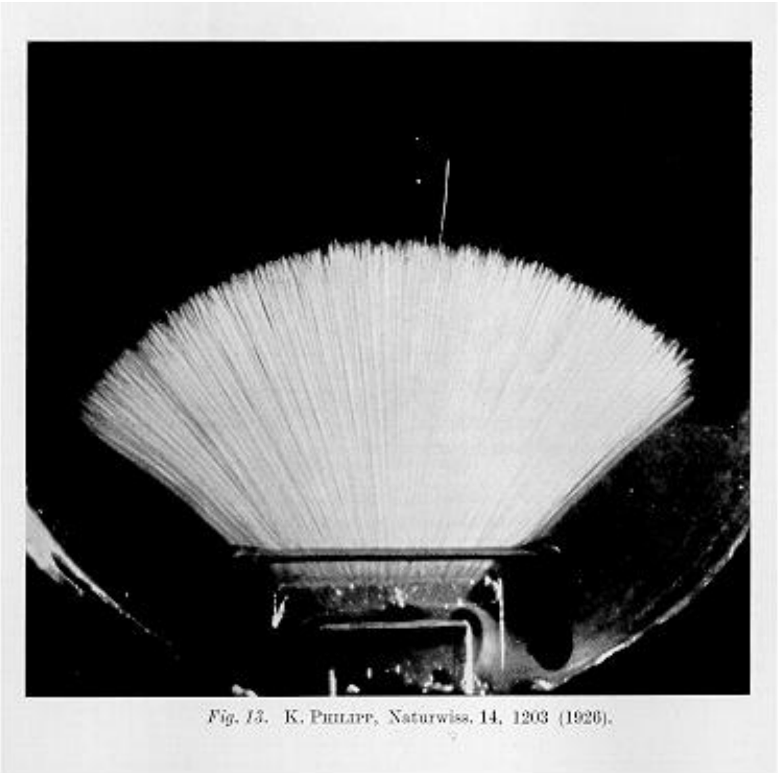
Cloud chamber

Probably the first particle detector.

Wilson wanted to study cloud formation and optical effects on moist air.
It is a chamber with super saturated vapor of water or alcohol.
When a particle traverses the environment droplets are formed along the track

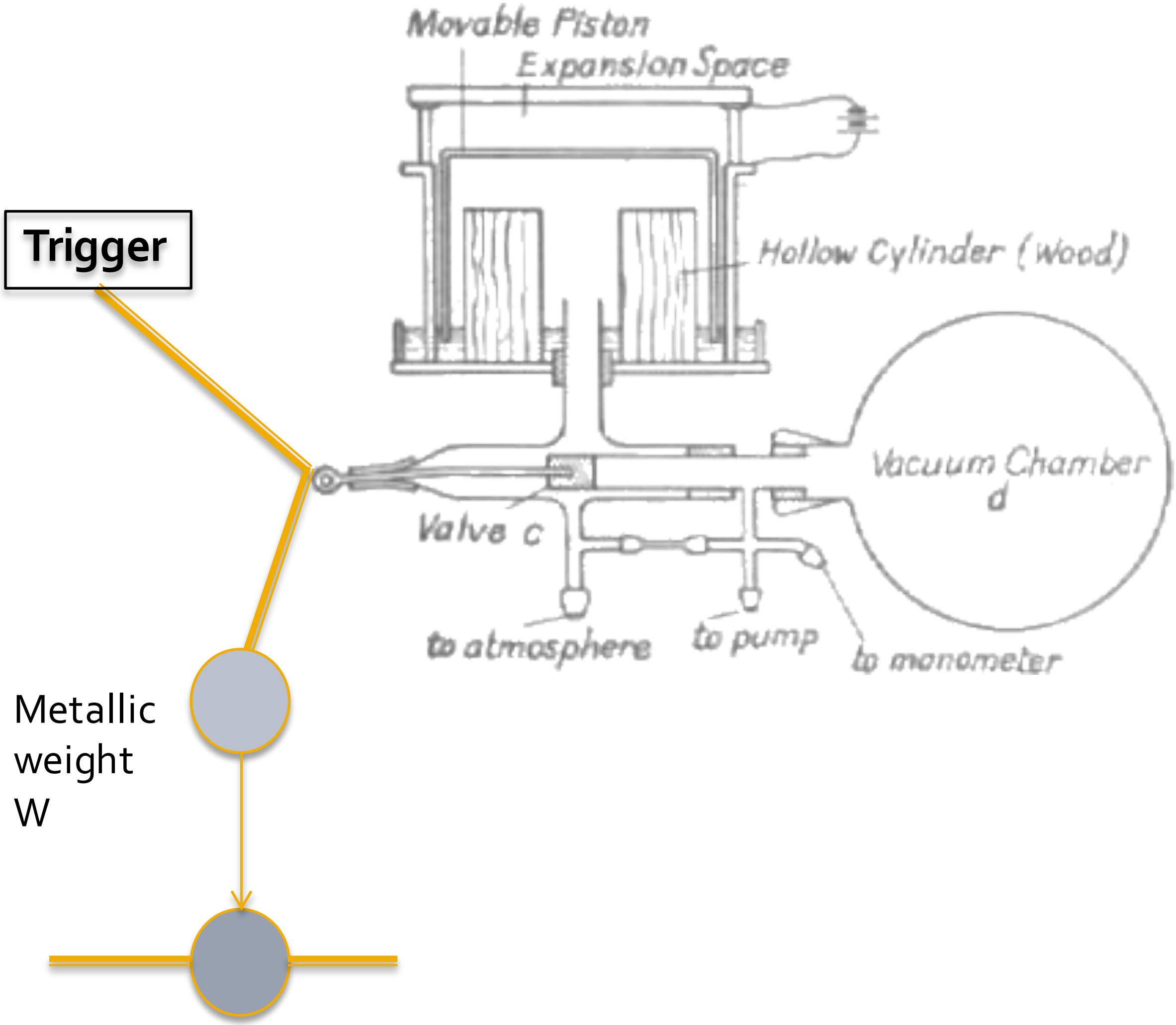


X-rays, Wilson 1912



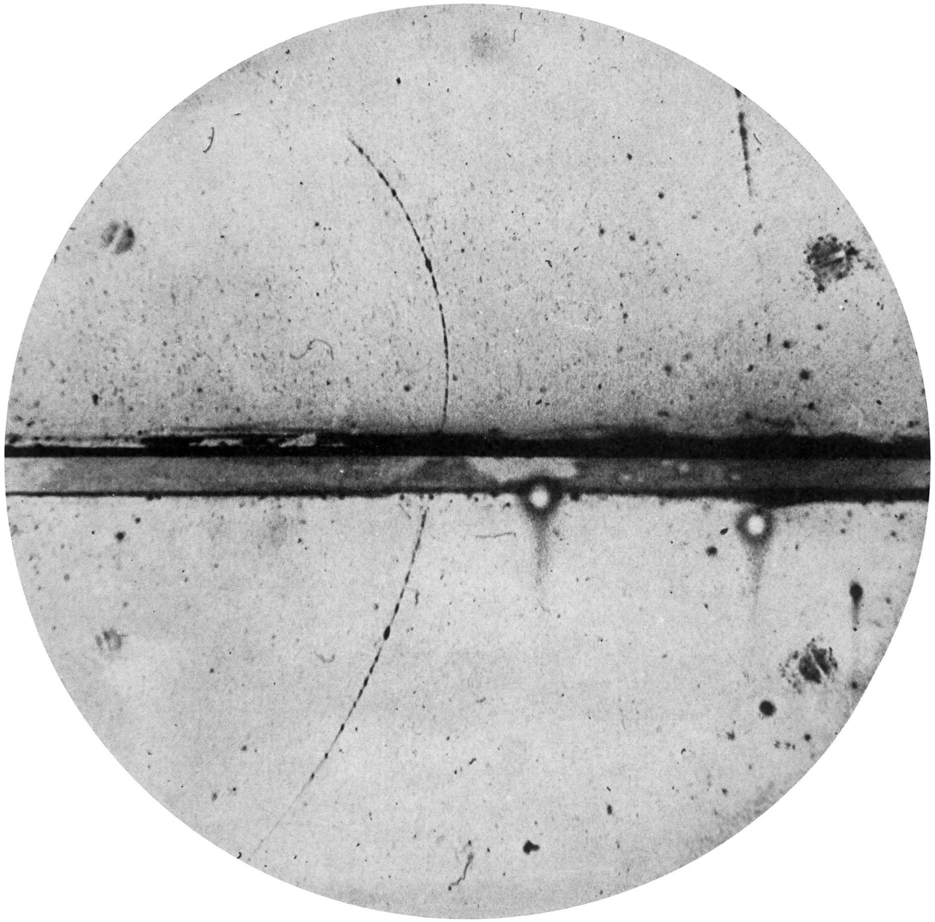
Alphas, Philipp 1926

Wilson's Cloud Chamber



1. A trigger frees a metallic weight that opens valve C when falling.
2. Connection to Vacuum chamber makes the movable piston to drop
3. After volume increase, the gas in Expansion Space is now supersaturated
4. The weight starts a kind of photographic "flash" that illuminates the chamber
5. Particles produce droplets that are registered by a camera.

Cloud Chambers: the positron

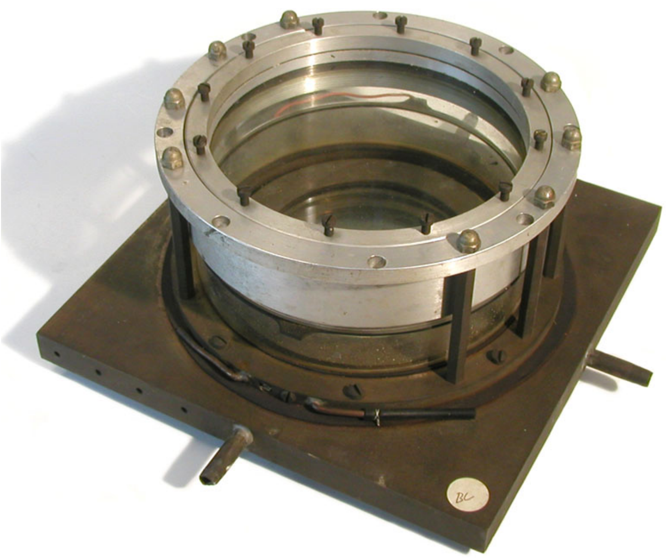


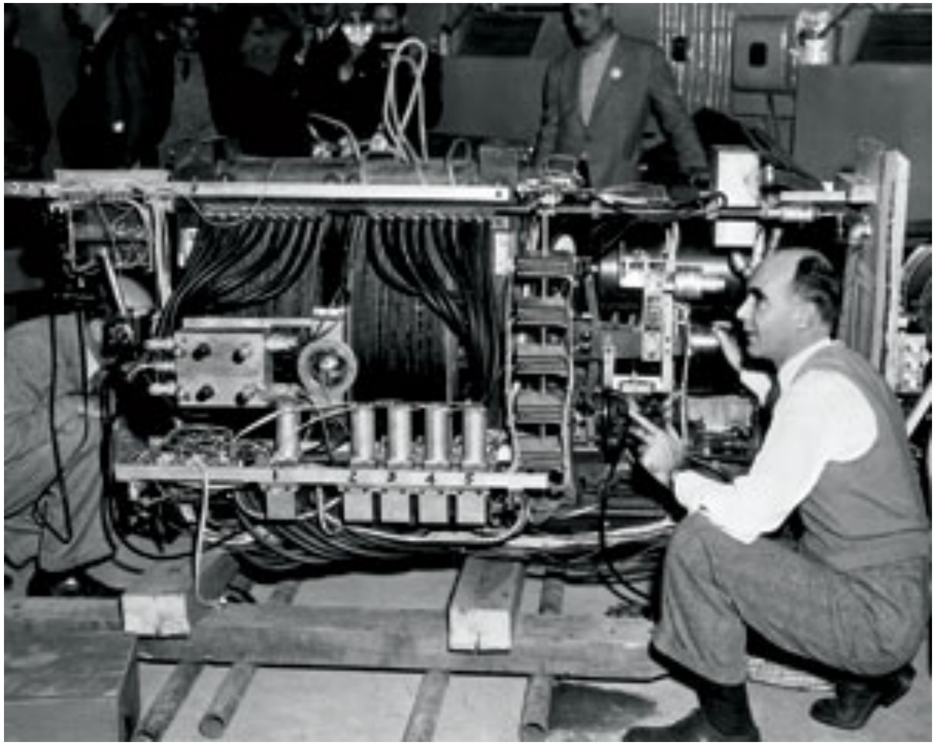
Positron discovery, Carl Andersen, 1933

Magnetic field 15000 Gauss, chamber diameter 15cm.
A 63 MeV positron passes through a 6mm lead plate, leaving the plate with energy 23MeV and a smaller radius.

The ionization of the particle, and its behaviour in passing through the foil are the same as those of an electron but it turns to the wrong side…

Cloud Chamber





Anderson's Cloud Chamber used to discover the positron

Cloud Chambers: muon discovery

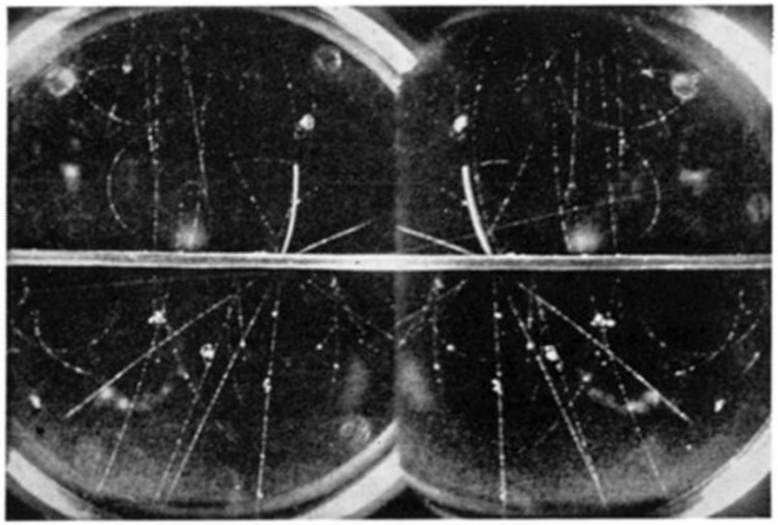


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to

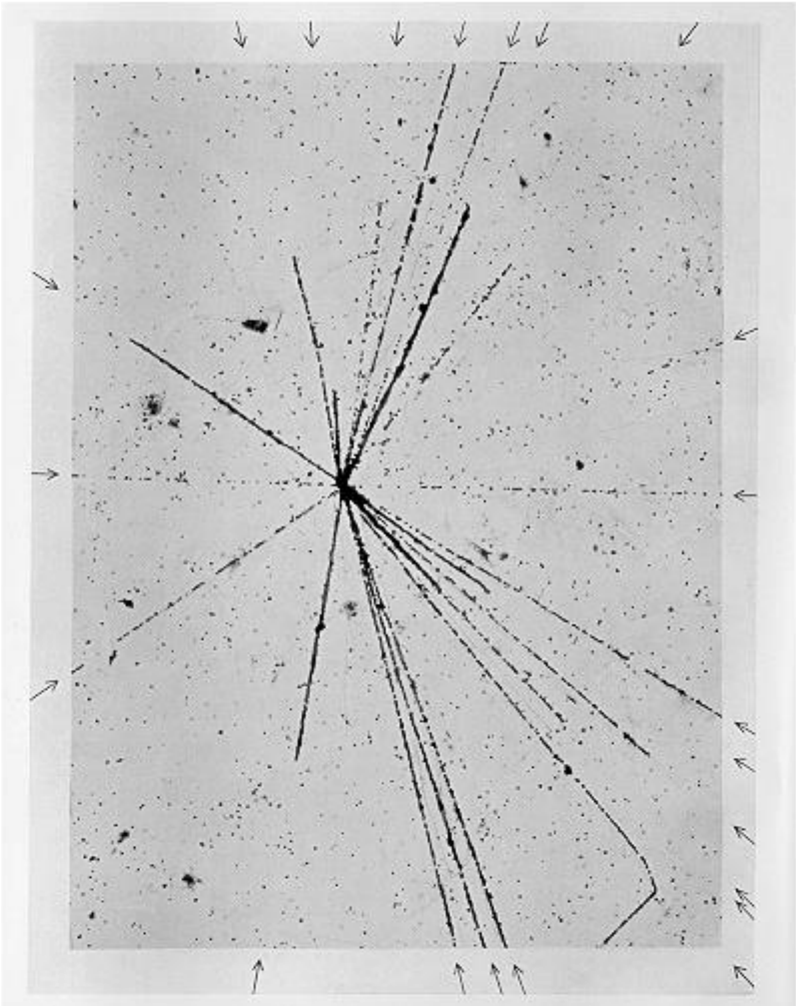
Anderson and Neddermeyer
Phys. Rev. 50 (1936) 263

Anderson and Neddermeyer observed for the first time particles that curved differently from electrons or protons given the energy inferred from the range.

They called this particle the "mesotron".

The existence of the muon was confirmed in 1937 by J.C. Street and C. Stevenson's Cloud Chamber

Nuclear Emulsions



'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 analysed 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 Emulsions

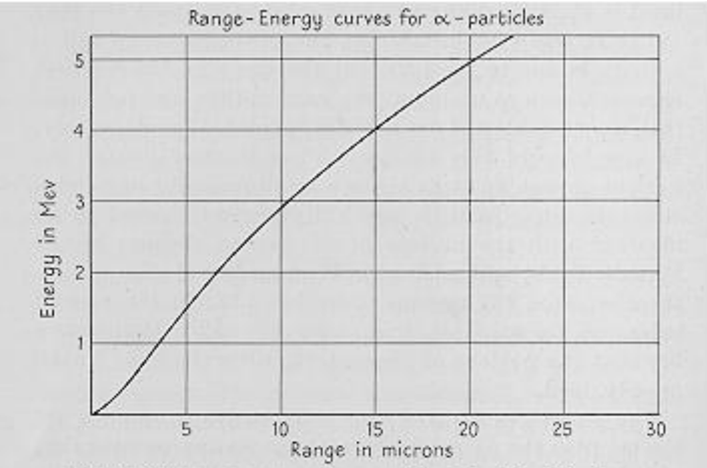


Fig. 2a. Range–energy curve for α-particles in the Ilford 'Nuclear Research' emulsions.

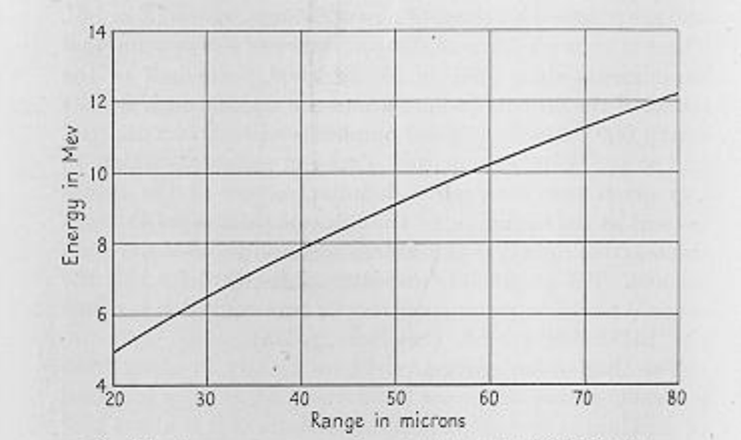


Fig. 2b. Range–energy curve for α-particles in the Ilford 'Nuclear Research' emulsions.

Emulsions are compact, have high density and produce a cumulative record.

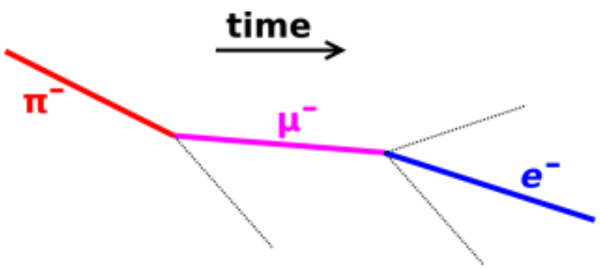
In 1939 Cecil Powell called the emulsion 'equivalent to a continuously sensitive high pressure expansion chamber'.

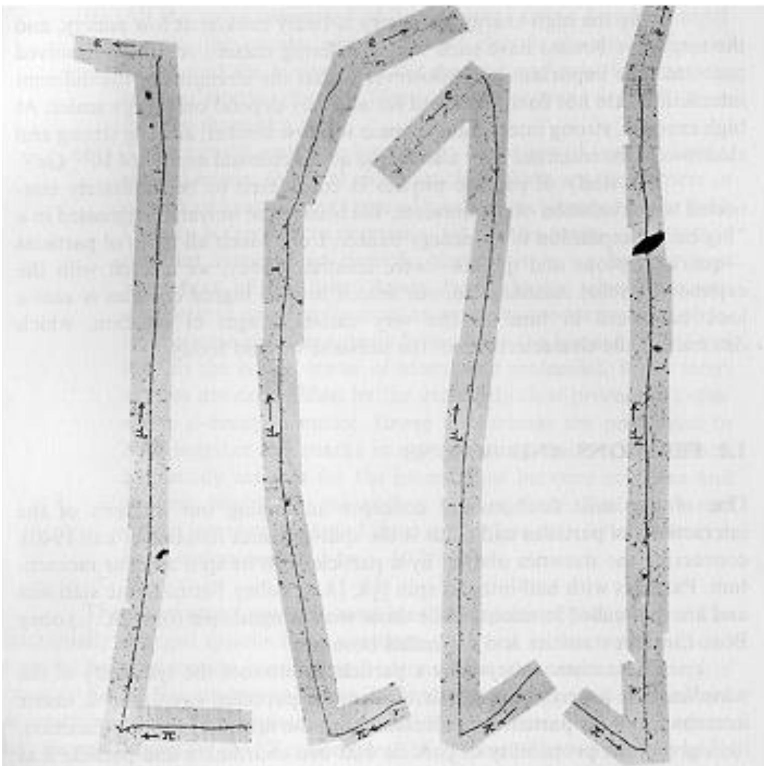
A result equivalent to the cloud chamber can be obtained with a picture 1000x smaller (emulsion density is about 1000x larger than gas at 1 atm).

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

Emulsion plates **had to be developed** before the tracks could be observed.

Emulsions: Discovery of the pion





Discovery of muon and pion

Discovery of the Pion:

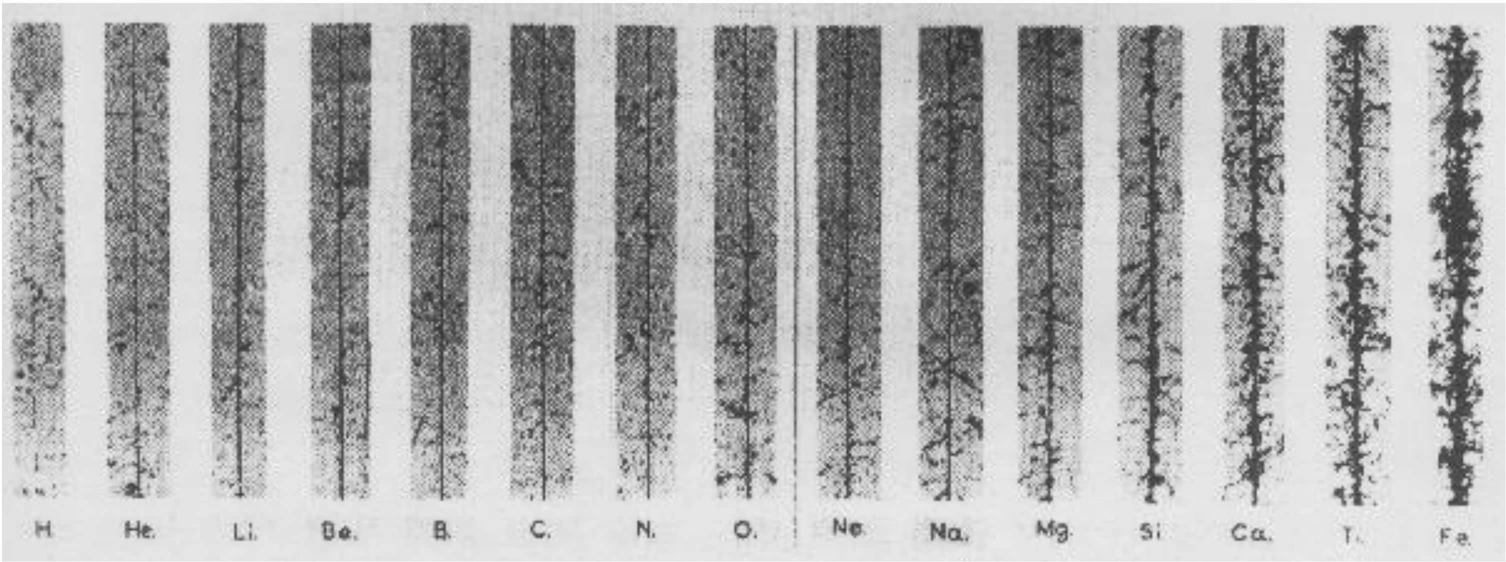
The muon was discovered in the 1930ies and was first believed to be Yukawa's meson that mediates the strong force.

The properties of the muon were 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.

Nuclear Emulsions

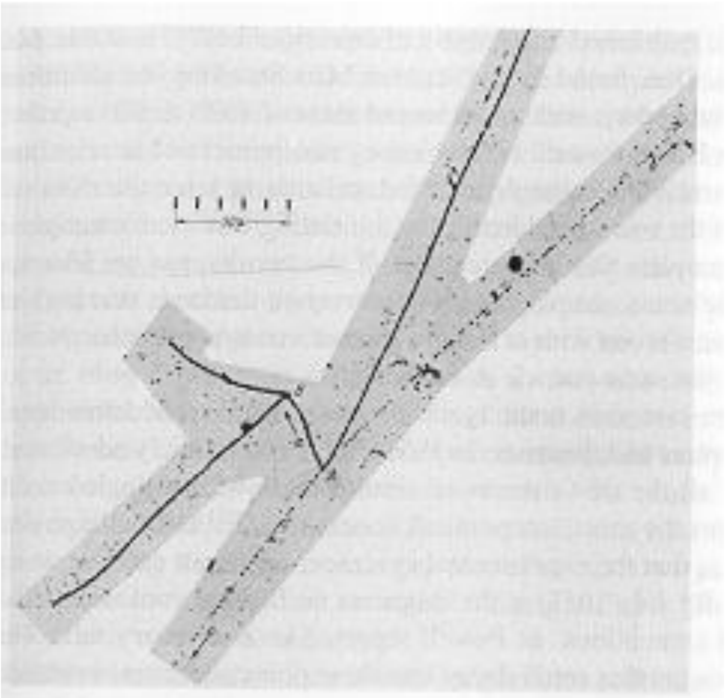
The cosmic ray composition was studied by putting emulsion plates on balloons at high altitudes



Energy loss is proportional to Z^2 of the particle

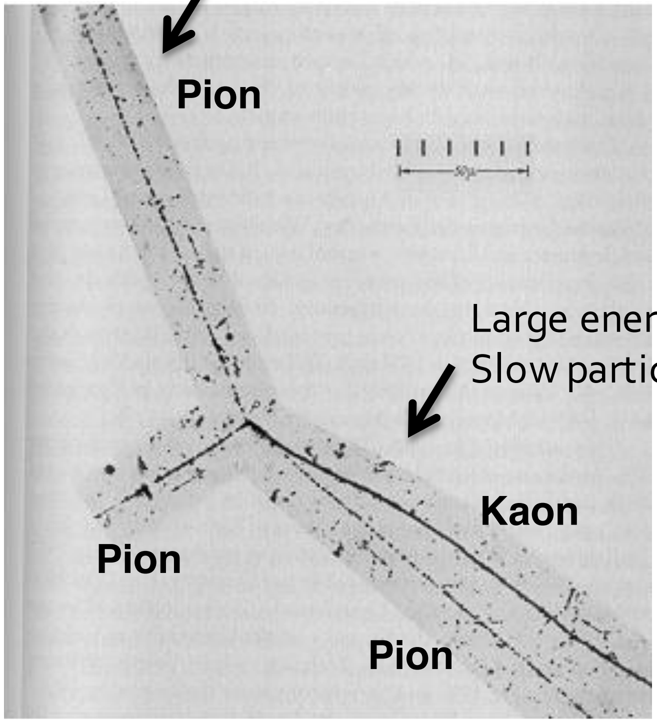
Nuclear Emulsions

First evidence of the Kaon into 3 pions was found in 1939



Small energy loss.
Fast particle

Large energy loss.
Slow particle



Bubble Chambers

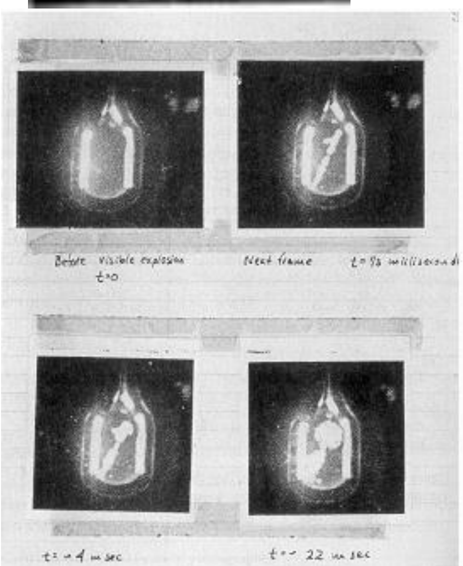


Figure 5.5 Bubble chamber movies (1952). Glaser first filmed distinct track

In the early 1950's **Donald Glaser** tried to build on the cloud chamber analogy:

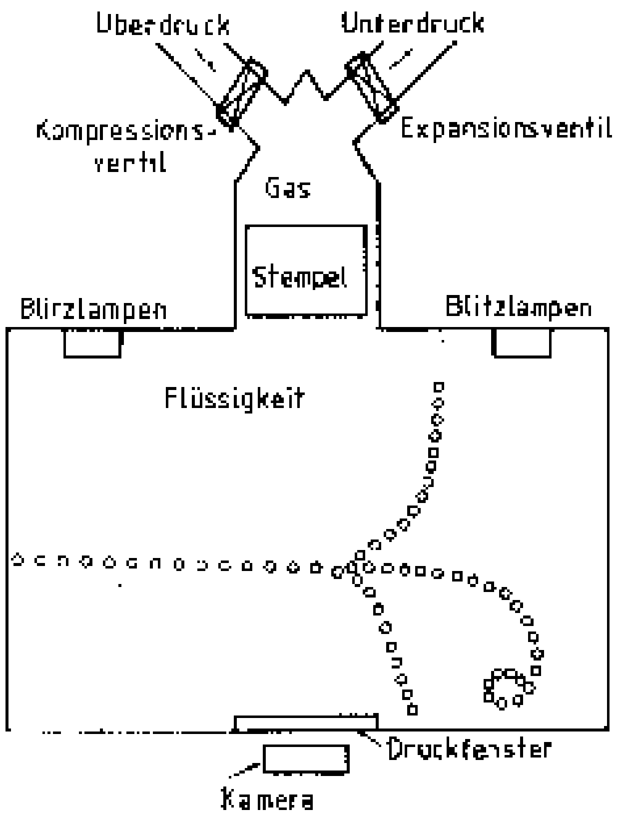
Instead of supersaturating a gas with a vapour one would superheat a liquid. A particle depositing energy along it's path would then make the liquid boil and form bubbles along the track.

In 1952 Glaser photographed first Bubble chamber tracks. **Luis Alvarez** was one of the main proponents of the bubble chamber.

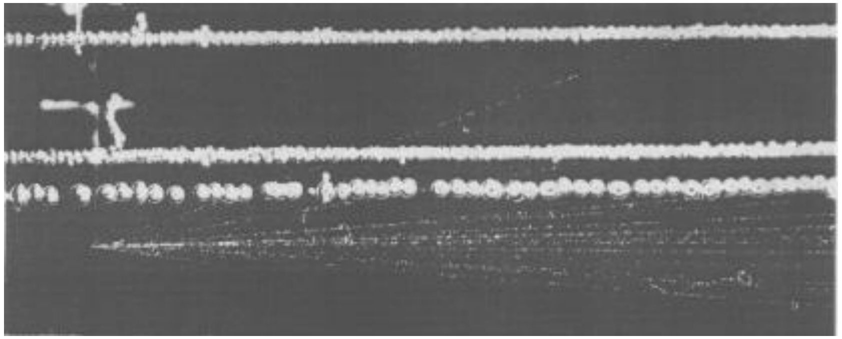
The size of the chambers grew quickly

1954:	2.5''(6.4cm)
1954:	4'' (10cm)
1956:	10'' (25cm)
1959:	72'' (183cm)
1963:	80'' (203cm)
1973:	370cm

Bubble Chambers



'old bubbles'



'new bubbles'

Contrary to Cloud Chambers, Bubble Chambers could not be triggered: the chamber has to be in superheated state when the particle arrives.

No useful for Cosmic physics, but in the 1950's **particle physics moved to accelerators** and it was possible to synchronize chamber compression with the arrival of the beam.

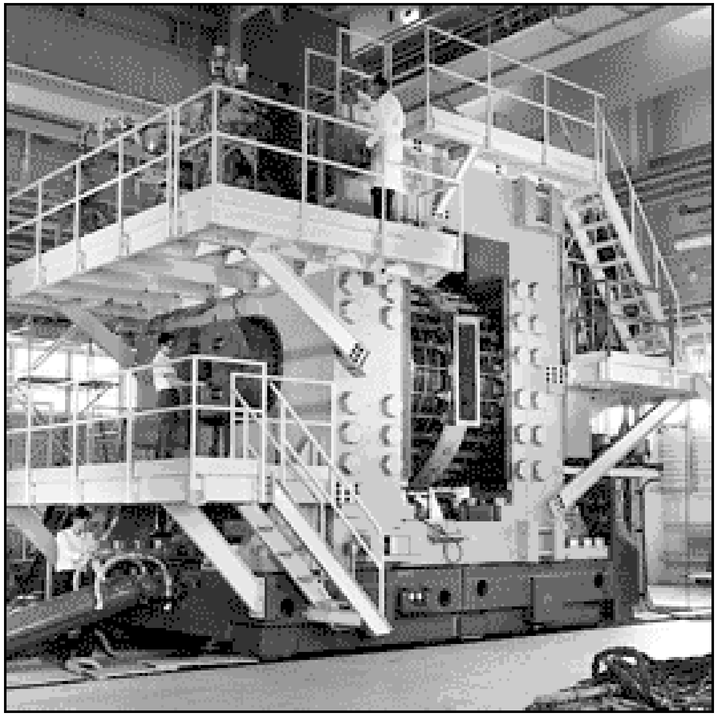
Bubble Chambers

In the bubble chamber, with a density about 1000 times larger that the cloud chamber, the liquid acts as the target and the detecting medium.

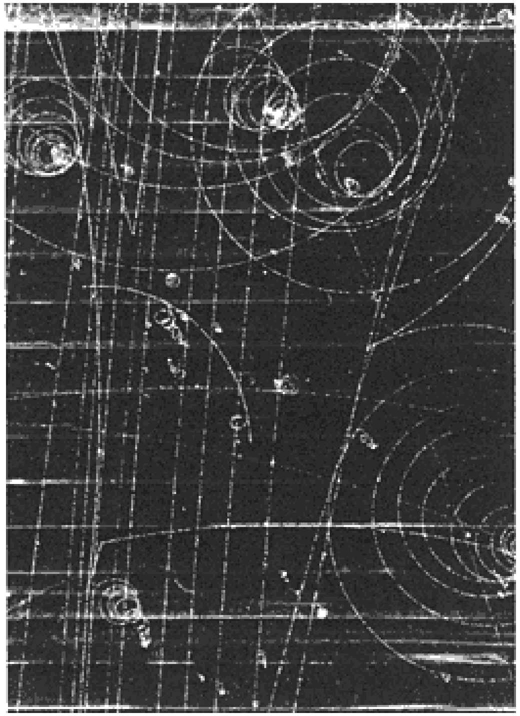
Figure:
A propane chamber with a magnet discovered the Σ° in 1956.

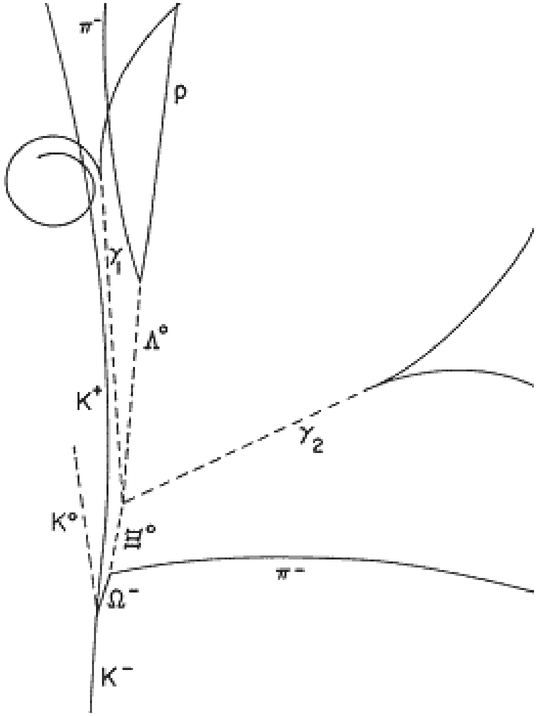
A 1300 MeV negative pion hits a proton to produce a neutral kaon and a Σ°, which decays into a Λ° and a photon. The latter converts into an electron-positron pair.

Bubble Chambers



The 80-inch Bubble Chamber



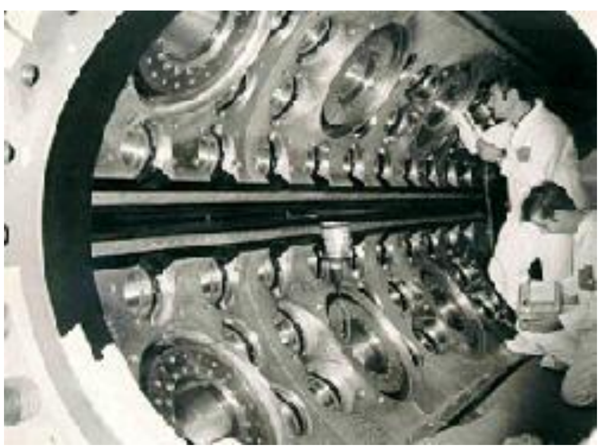


BNL, First Pictures 1963, 0.03s cycle

Discovery of the Ω^- in 1964

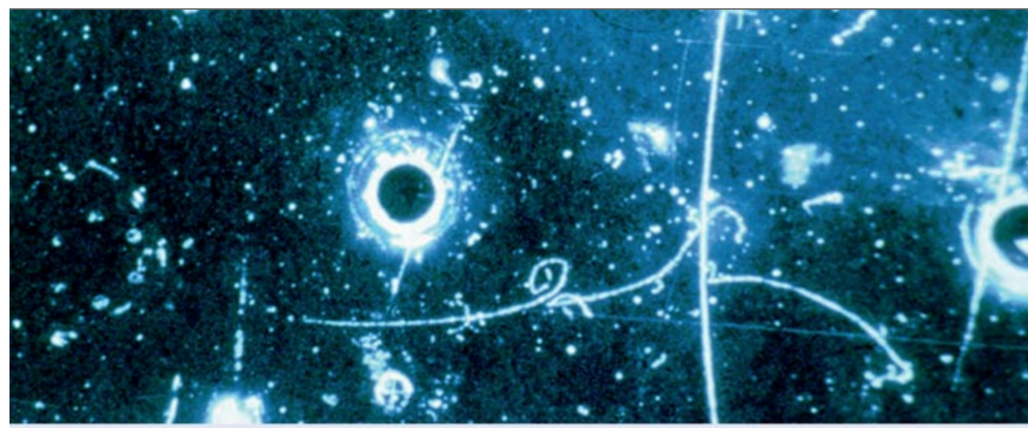
Bubble Chambers

Can be seen outside the Microcosm Exhibition

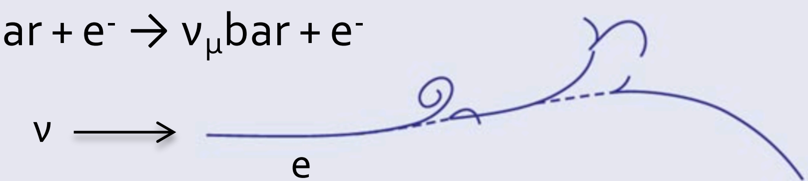


Gargamelle, a very large heavy-liquid (freon) chamber constructed at Ecole Polytechnique in Paris, came to CERN in 1970.
It was 2 m in diameter, 4 m long and filled with Freon at 20 atm.

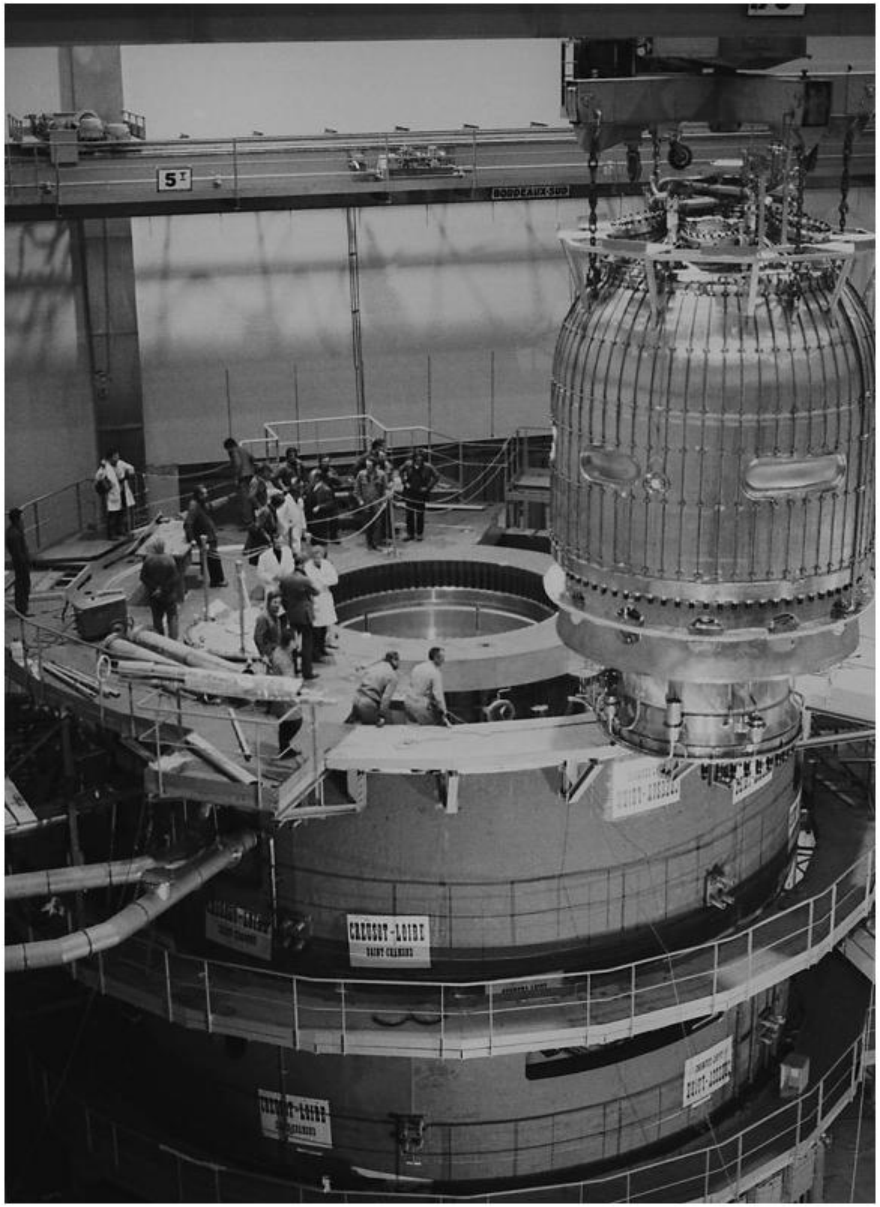
With a conventional magnet producing a field of almost 2 T, Gargamelle in 1973 was the tool that permitted the discovery of neutral currents.



$\nu_\mu bar + e^- \rightarrow \nu_\mu bar + e^-$



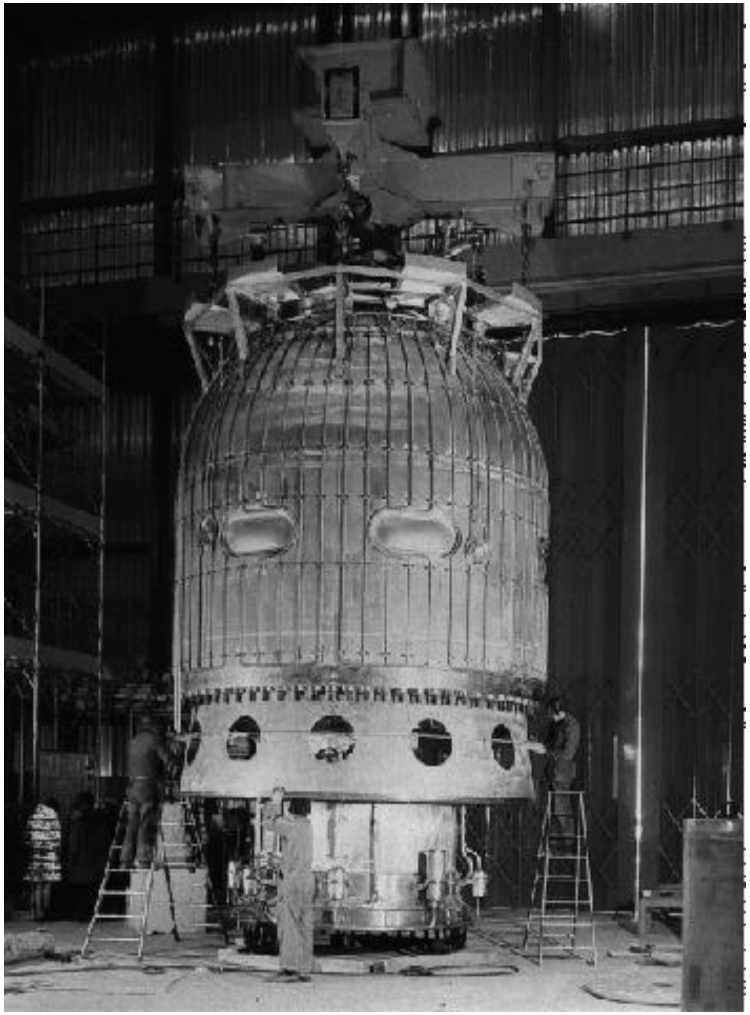
Bubble Chambers



The Big European Bubble Chamber

3.7 m bubble chamber at CERN, equipped with the largest superconducting magnet in the world

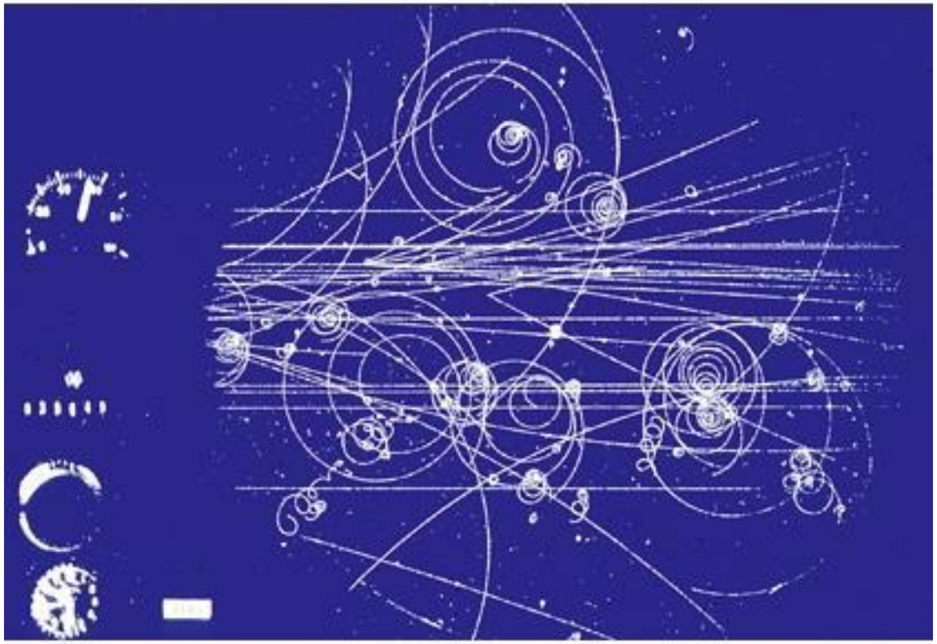
Bubble Chambers



Can be seen outside the Microcosm Exhibition

3.7 meter hydrogen bubble chamber at CERN, equipped with the largest superconducting magnet in the world.

During its working life from 1973 to 1984, the "Big European Bubble Chamber" (BEBC) takes over 6 million photographs.



Bubble Chambers

- The excellent position resolution (5μm) and the fact that target and sensing element are the same (in the H chambers) makes the Bubble Chamber unbeatable for reconstruction of complex decay modes.
- The drawbacks:
  - Low rate capability (few tens/second). Eg. LHC produces ~10^9 collisions/s
  - Cannot be triggered selectively, so each interaction should be photographed.
  - Images had to be analysed by "operators".
- This is why electronics detectors took over in the 1970's.

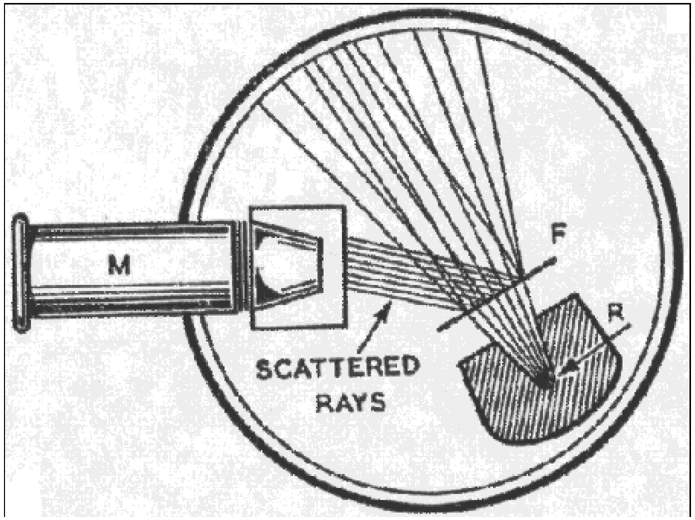
LOGIC AND ELECTRONICS

Early days of "Logic Detectors"

Scintillating Screen:

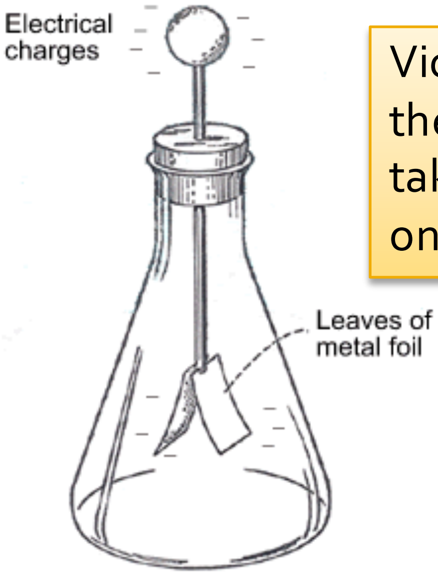
Rutherford Experiment 1911: Zinc Sulfide screen was used as detector.

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



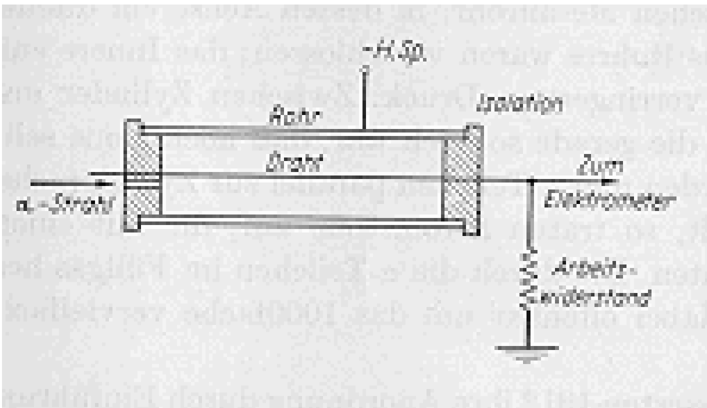
Electroscope:
When the electroscope is given an electric charge the two 'wings' repel each other and stand apart.

Radiation can ionize some of the air in the electroscope and allow the charge to leak away, as shown by the wings slowly coming back together.

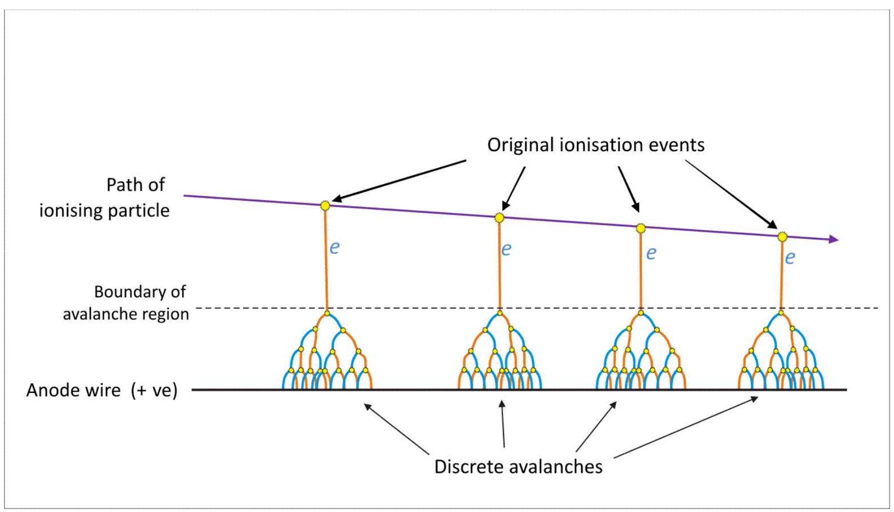


Victor Hess discovered the Cosmic Rays by taking an electroscope on a Balloon

Geiger & Rutherford



Rutherford and Geiger 1908



In 1908, Rutherford and Geiger developed an electric device to measure alpha particles.

The alpha particles ionize the gas, the electrons drift to the wire in the electric field and they multiply there, causing a large discharge which can be measured **by an electroscope**.

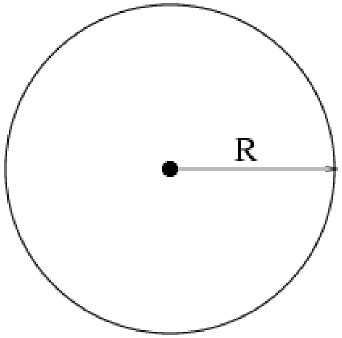
They saw "random discharges" in the absence of alphas.

This was interpreted as "instability" so the device wasn't used much.

Detector + Electronics

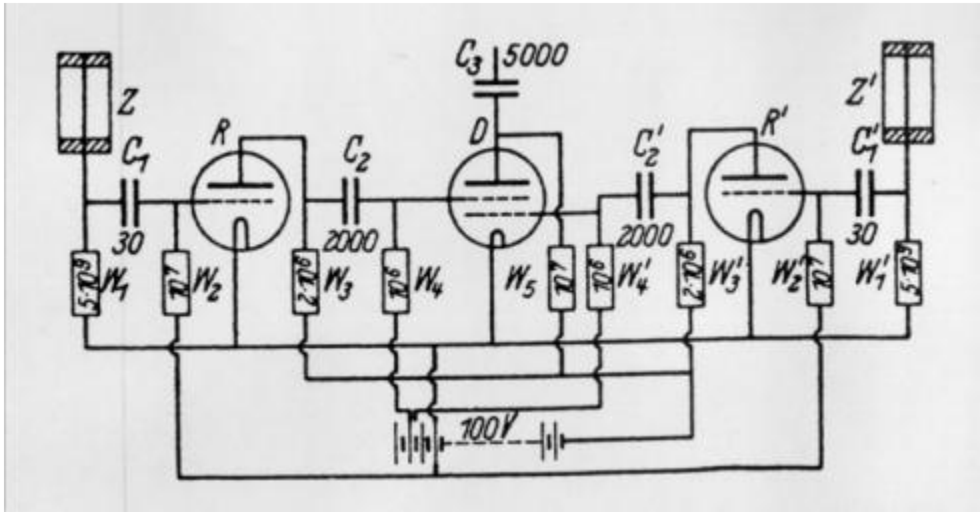
In 1928 Walther Müller started to study the spontaneous discharges systematically and found that they were actually caused by cosmic rays discovered by Victor Hess in 1911.

By realizing that the wild discharges were not a problem of the counter, but were caused by cosmic rays, the Geiger-Müller counter went, without altering a single screw from a device with 'fundamental limits' to the most sensitive instrument for cosmic rays physics.



'Zur Vereinfachung von Koinzidenzzählungen'
W. Bothe, November 1929

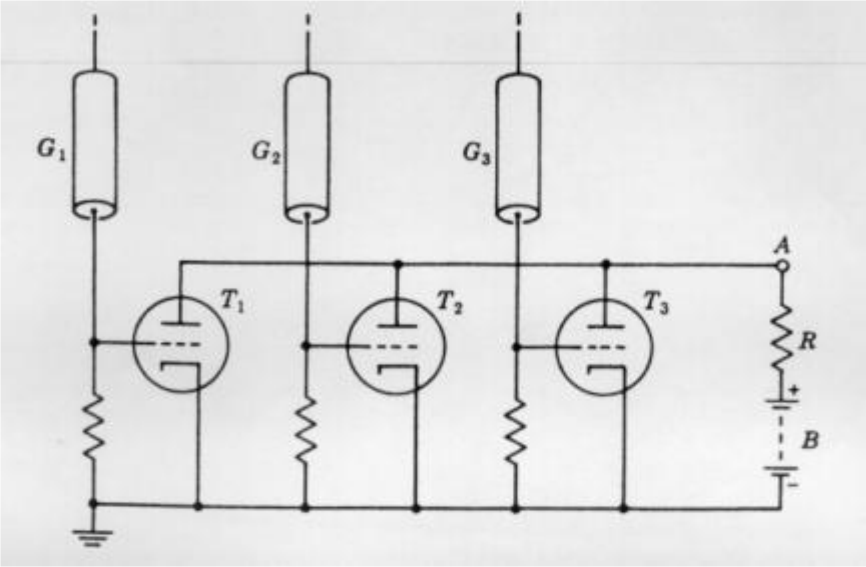
Coincidence circuit for 2 tubes

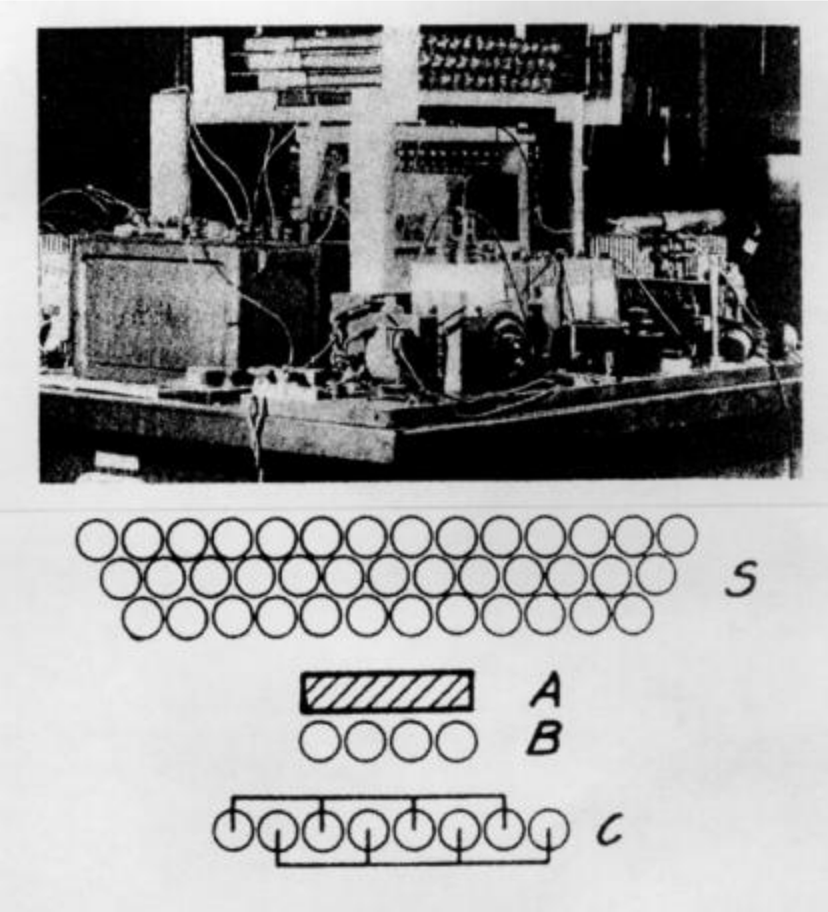


Detector + Electronics

Cosmic ray telescope 1934

Rossi 1930: Coincidence circuit for n tubes





The Scintillator counter

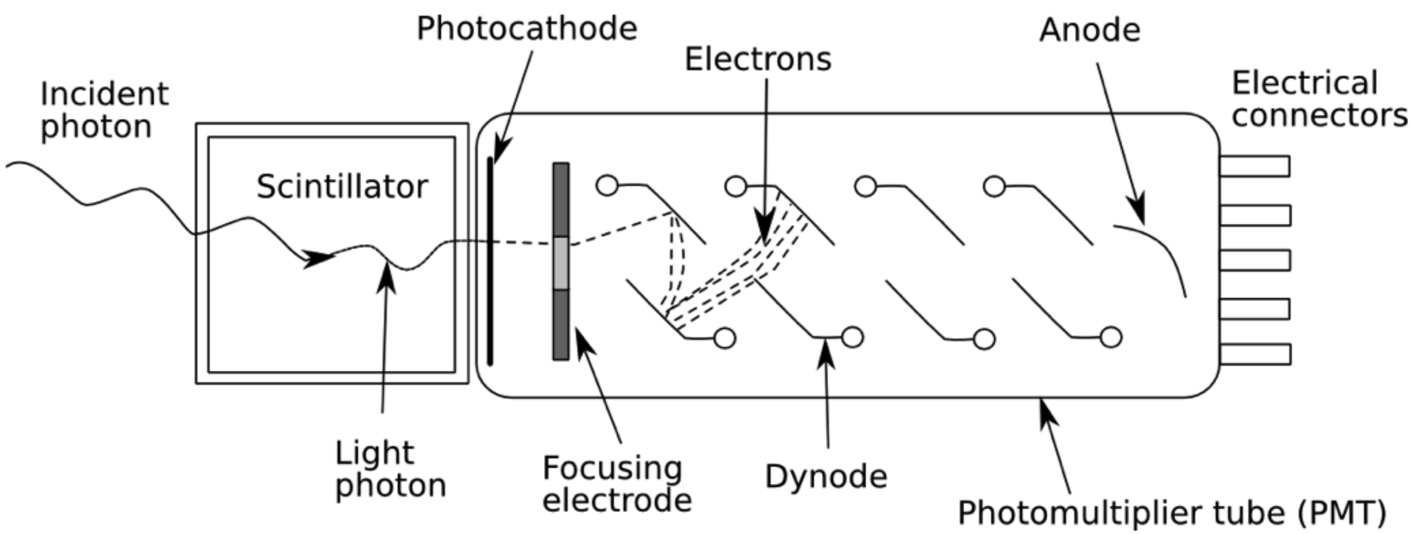
W. Crookes, 1903

First scintillators for science: spinthariscope in ~1903 (visual counting)

Scintillator detectors see a breakthrough in the 1940s.

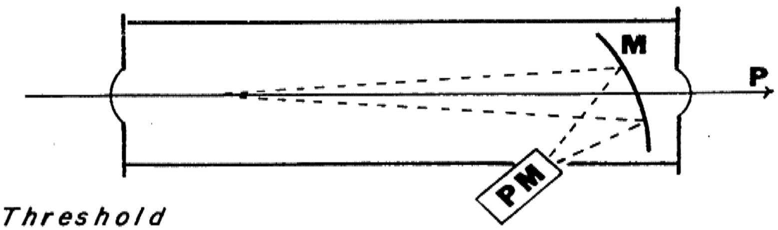
While Sir Samuel Curran was working in Berkeley, USA, on the Manhattan project in 1944 he needed a better method for the detection of small quantities of uranium.

He combined a scintillator (Zinc Sulphide) with a photomultiplier (known since 1930) and produced a working detector: a **Scintillator Counter**



Cerenkov Detectors

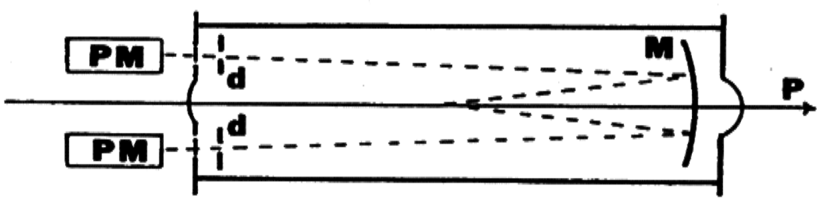
Threshold Cerenkov Counter



Threshold

For a particle with a given mass, it is used as a **momentum threshold counter**

Differential Cerenkov Counter



Differential

For a fixed momentum, it only selects particles with a given velocity (given by the angle) , it is a **"mass counter"**

The "n" of the gases changes with the pressure, so it is a sort of knob to change the thresholds on momentum or mass.

Logic Detectors

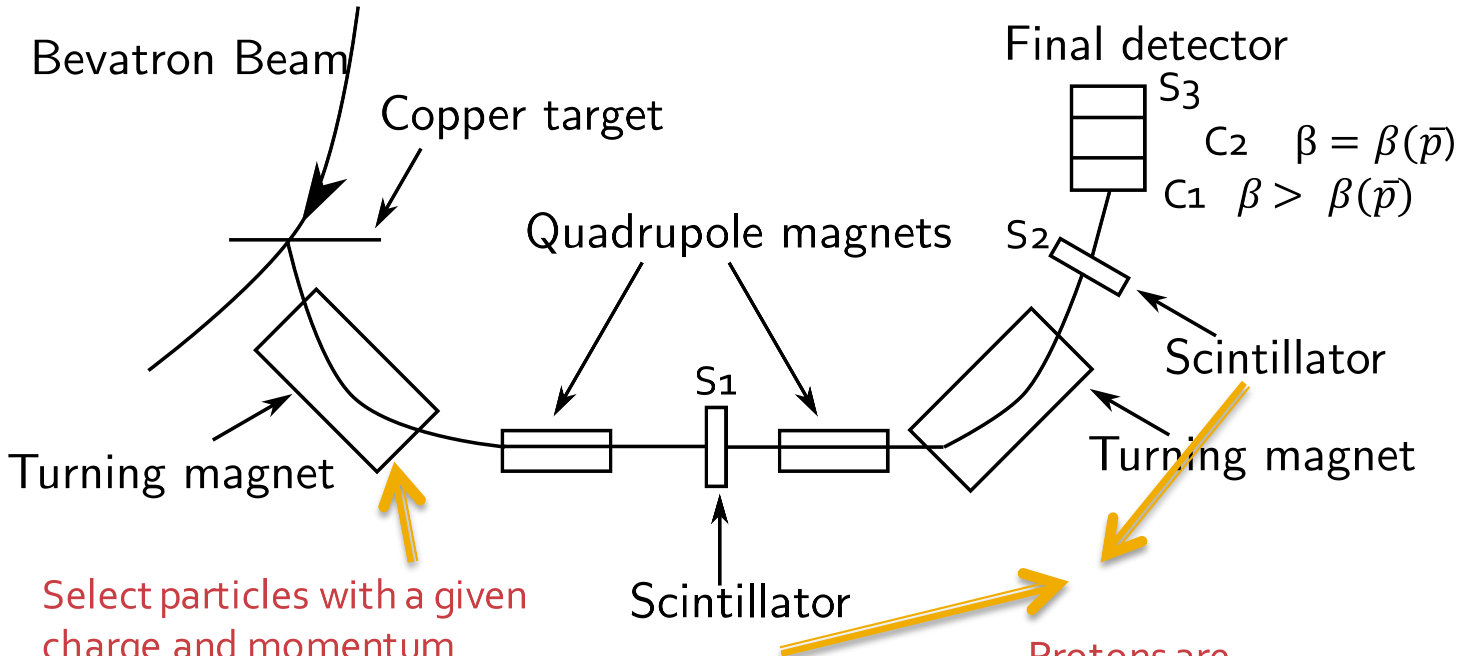
- Scintillator counters and Cerenkov detectors exploded into use in the 1940's
- This was mainly due to the electronics revolution that begun during World War II.
- High-gain photomultiplier tubes, amplifiers, scalers, pulse height analysers saw the light during this epoch.
- A nice example is the experiment of the Antiproton discovery

Antiproton discovery

1955, at the Bevatron in Berkeley.
Segrè and Chamberlain

Protons

Two Cerenkov counters to trigger on a speed compatible with antiproton, and a third scintillator



Select particles with a given charge and momentum

Protons are slower than pions. Set a Δt compatible with a proton

Antiproton discovery

Evidence seen on electronics.

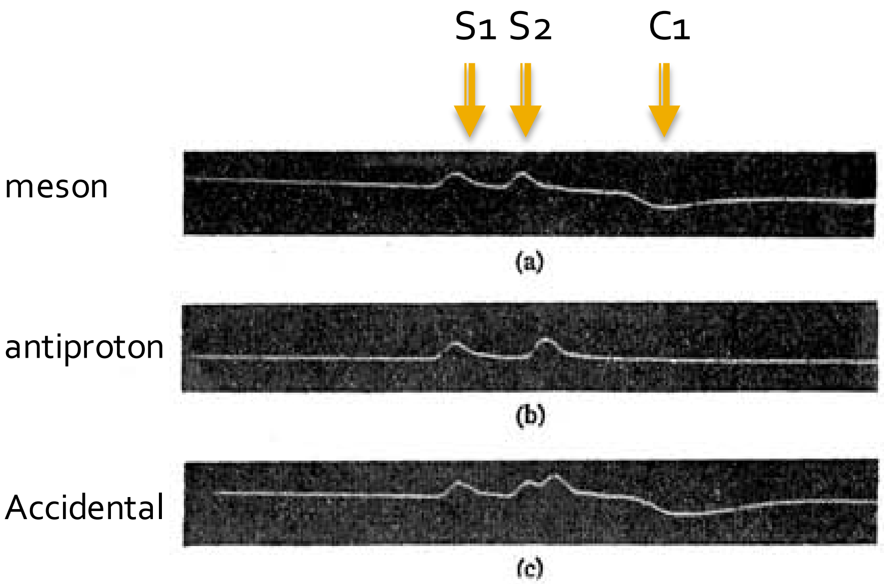


FIG. 2. Oscilloscope traces showing from left to right pulses from $S1$, $S2$, and $C1$. (a) meson, (b) antiproton, (c) accidental event.

A second group (G. Golhaber & E. Amaldi) used emulsions obtained with same experiment to look for proton-antiproton annihilation and to measure mass.

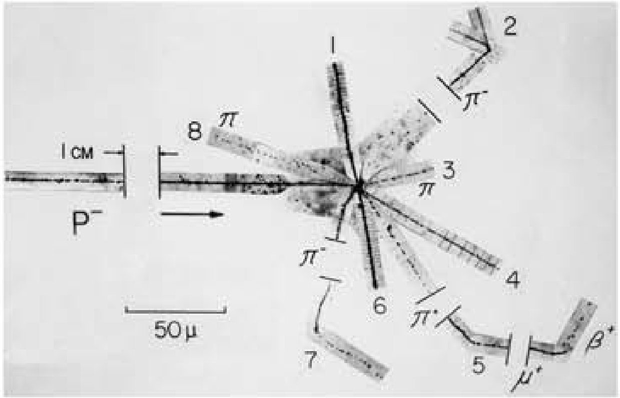
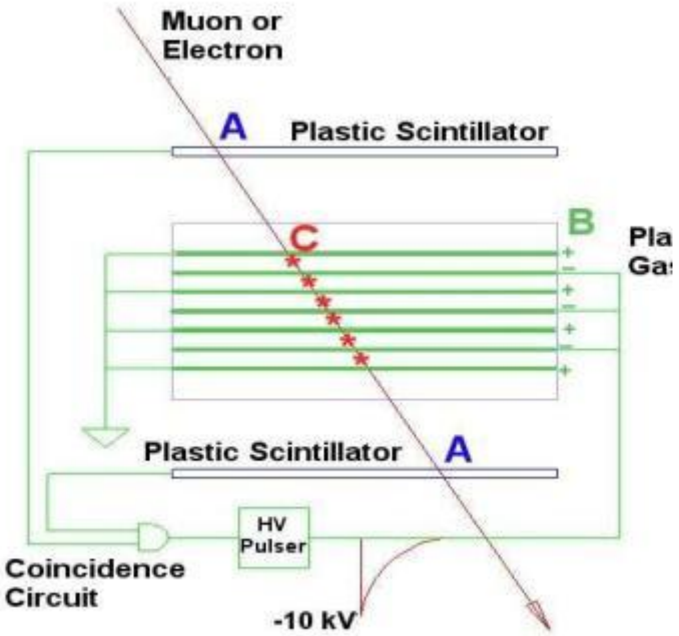


FIG. 2. Reproduction of the P^- star. The description of the prongs is given in Table II. The star was observed by A. G. Ekspong and the photomicrograph was made by D. H. Kouns.

TABLE I. Mass measurements.

Method	Residual range cm of emulsion	Mass M/M_p
Ionization–range	2, 5.5, and 12	0.97 ±0.10
Scattering–range (constant sagitta)	0–1	0.93 ±0.14
Momentum–range	12.13+0.12 (air and helium equivalent)	1.025±0.037
Weighted mean		1.013±0.034

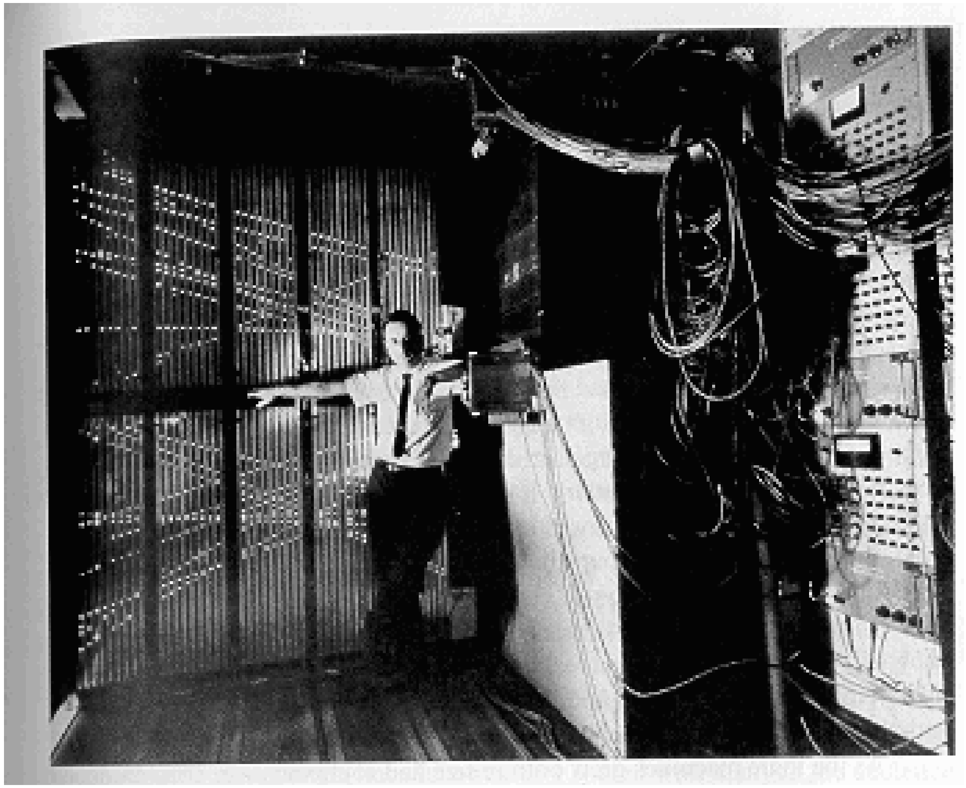
Spark Counters



The Spark Chamber was developed in the early 60ies.

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

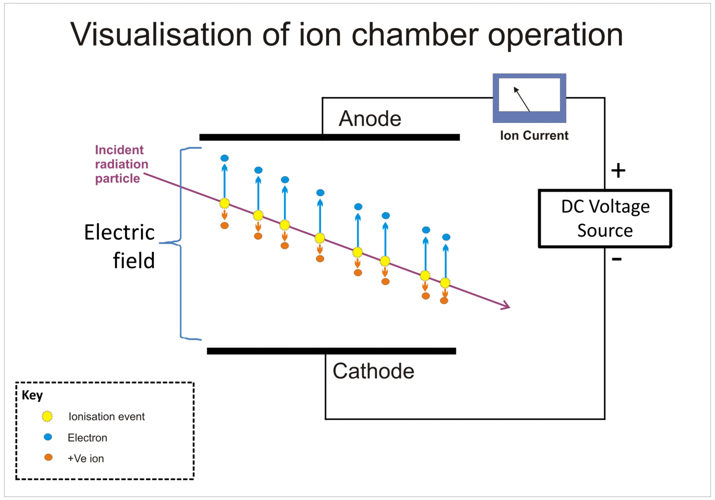
1988 Nobel Prize in Physics

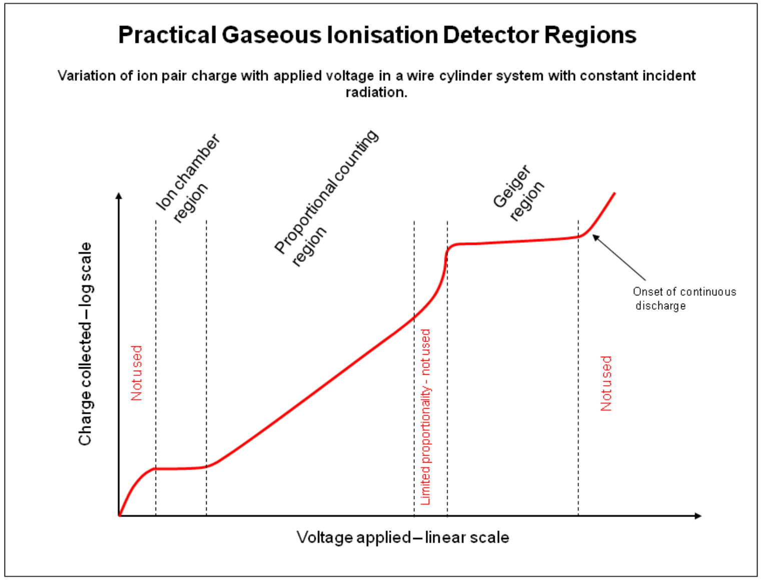


A charged particle traverses the detector and leaves an ionization trail.

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

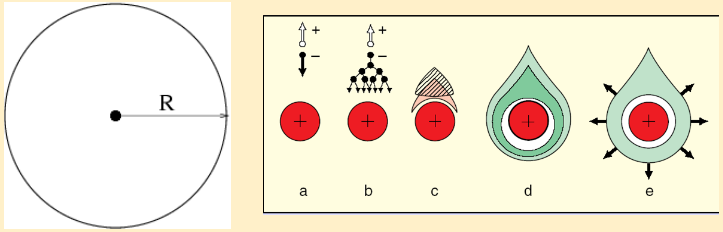
Gas detectors



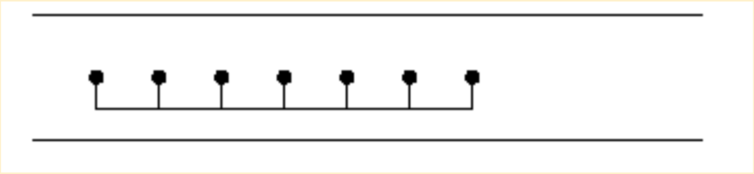


If voltage not too high, the charge seen is proportional to the energy deposited.

Tube, Geiger-Müller, 1928



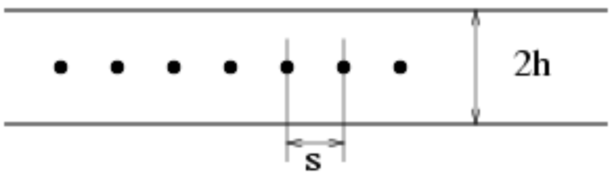
Multiwire geometry, H. Friedman, 1949
(all wires connected)

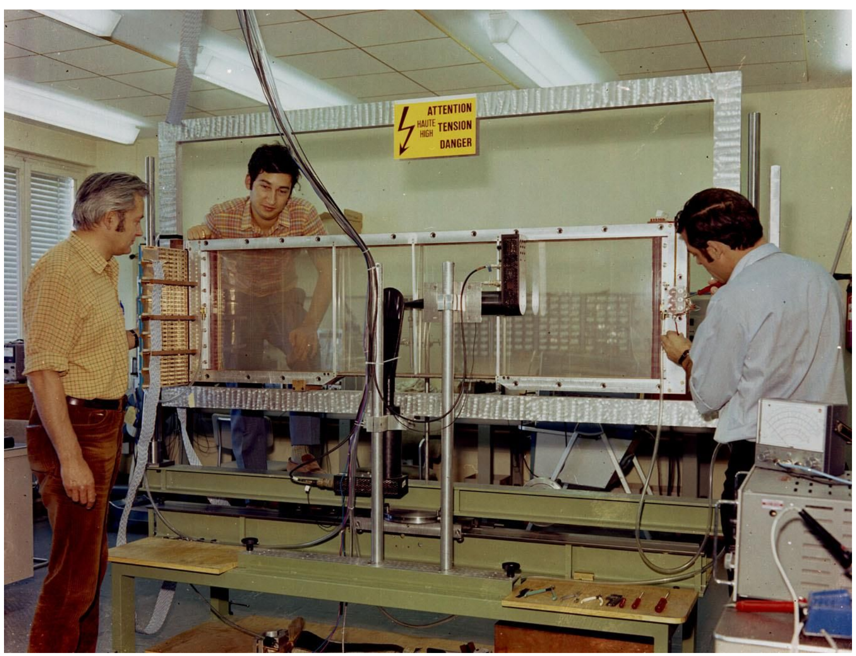


Charpak's MWPC

The multi wire proportional chamber was a real break-through that deserved the Nobel Prize in Physics in 1992.

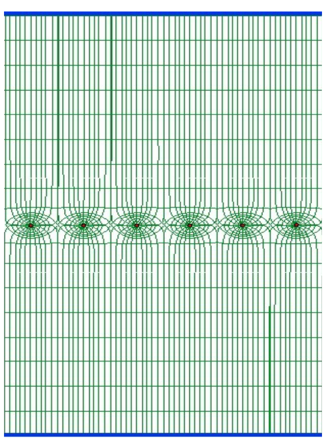
Multiwire proportional chamber with single wire readout, G. Charpak, 1968.





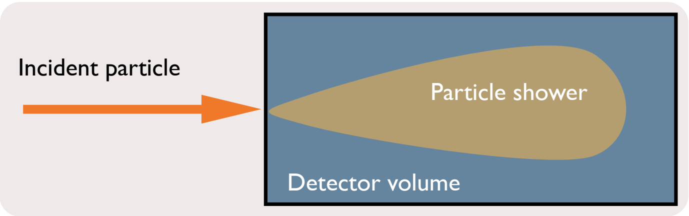
Individual wire readout: A charged particle traversing the detector leaves a trail of electrons and ions.

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 on the wire which can be read out by an amplifier.

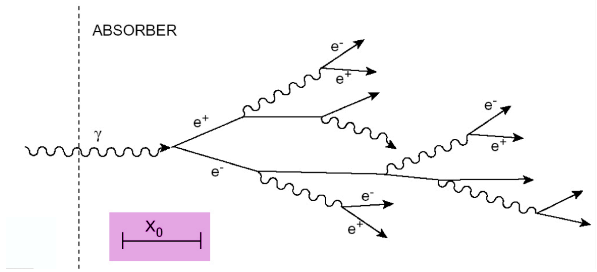


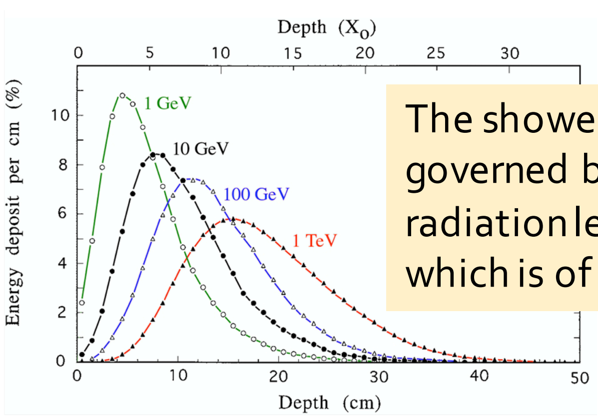
Measuring Energy

We measure energy by total absorption of the particles. Scintillators used as first “calorimeters” (shower counters).



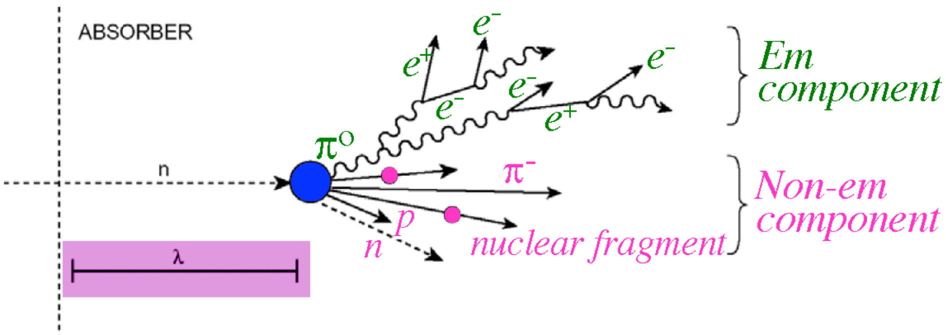
Electromagnetic Showers





The shower is governed by the radiation length which is of order 1cm

Hadronic showers



Hadronic showers are governed by the nuclear interaction length which is typically ~20 cm.

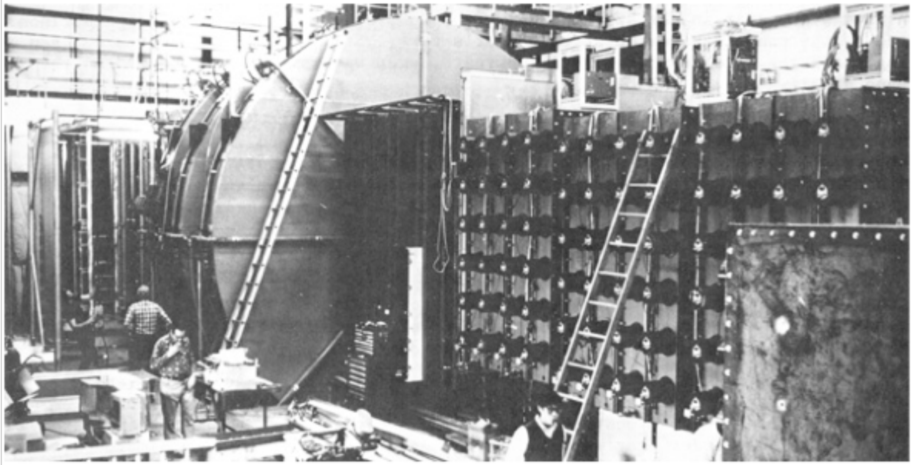
It takes tons to contain hadronic showers.

Have both EM and Hadronic component

Measuring energy

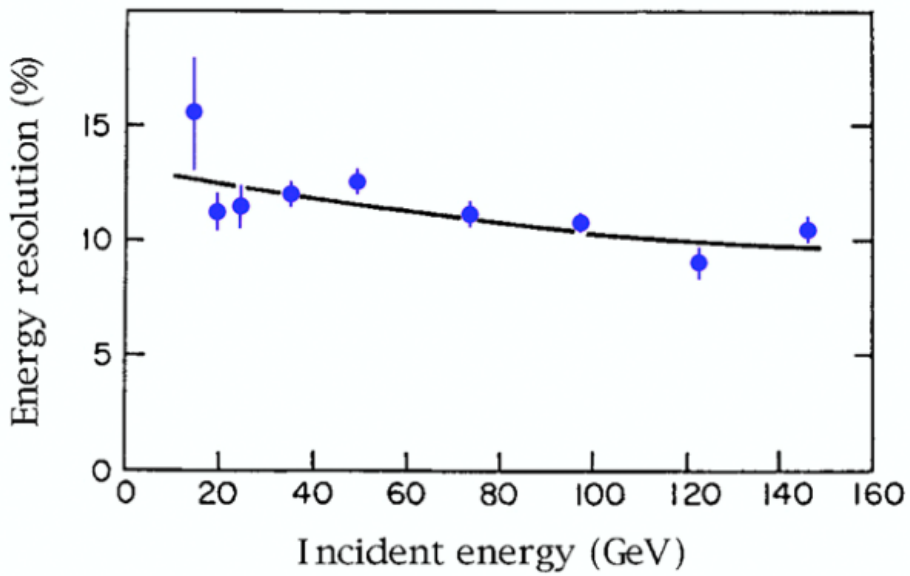
Energy resolution of a homogeneous hadron calorimeter

(60 tonnes of liquid scintillator)



Statistical processes are NOT the limiting factor here. Resolution is limited by fluctuations in invisible energy losses, related to e/h ~1.7

From: NIM 125 (1975) 447



Measuring energy

- In the 70s, calorimeters took on new tasks
  - High energy neutrino experiments as target and trigger (total energy)
  - Collider experiments: Energy flow (missing E_T , jets)
  - General: Particle ID (e, γ, μ, ν)
- Only in the mid 80s hadronic calorimeters were understood and simulated properly.
- More in tomorrow´s talk…

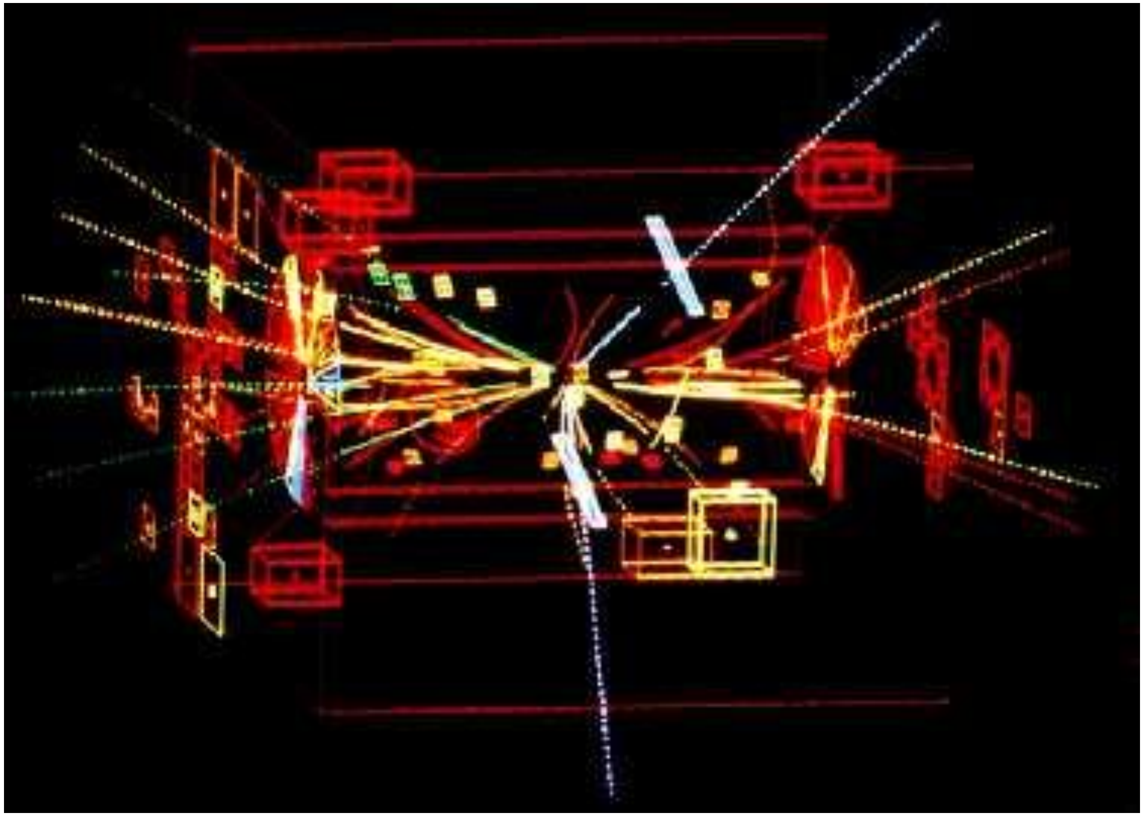
THE ELECTRONIC IMAGE

During the 1970's the image and logic devices merged into the electronic imaging devices

W/Z discovery at UA1/UA2, 1983

UA1 used a very large wire chamber.

Can now be seen in the CERN Microcosm Exhibition

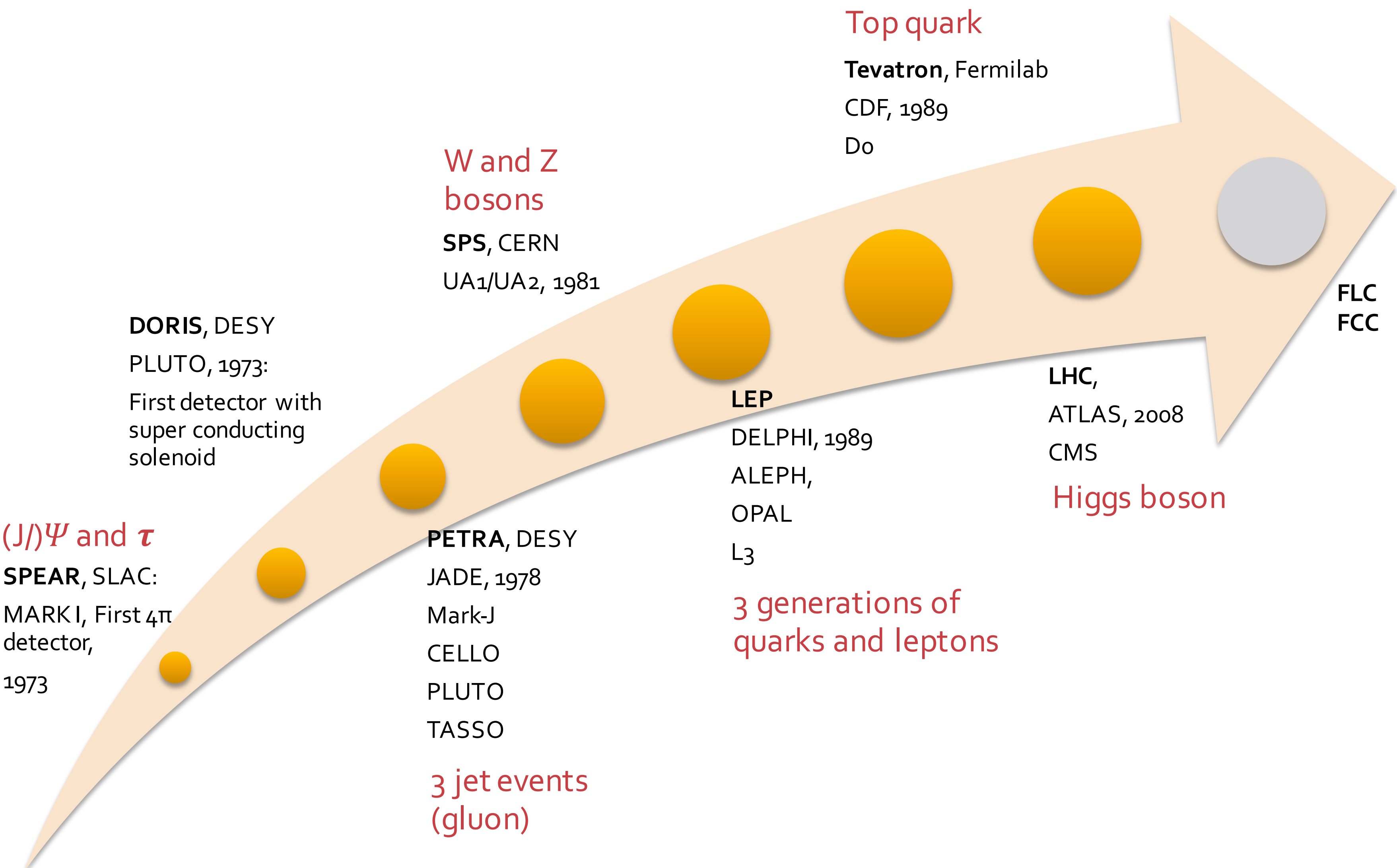


This computer reconstruction shows the tracks of charged particles from the proton-antiproton collision. The two white tracks reveal the Z's decay. They are the tracks of a high-energy electron and positron.

Electronic imaging

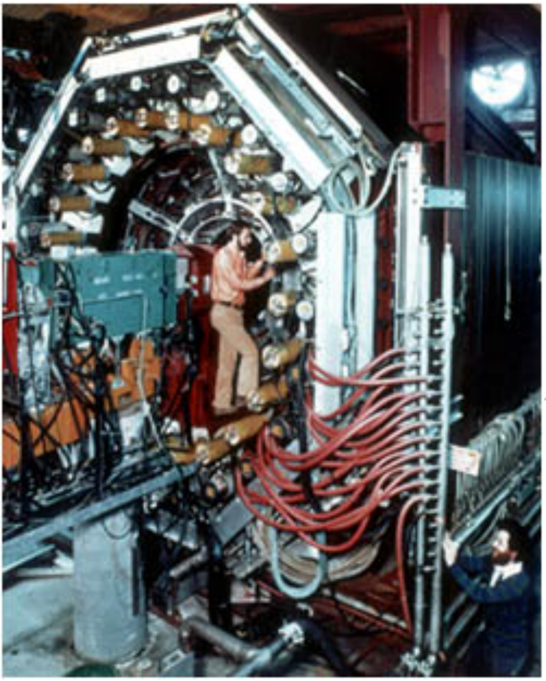
- In the 1960's bubble chamber experiments are replaced by "spectrometers" in the "forward region" of fixed target experiments.
  - Momentum from Lorentz Force
  - Energy (mass) from Time of Flight or dE/dx
  - Shower Counters (scint.) for gammas mainly from π^0 decays
- First 4π detectors appear in the beginning of the 1970's

Particle detectors for colliders



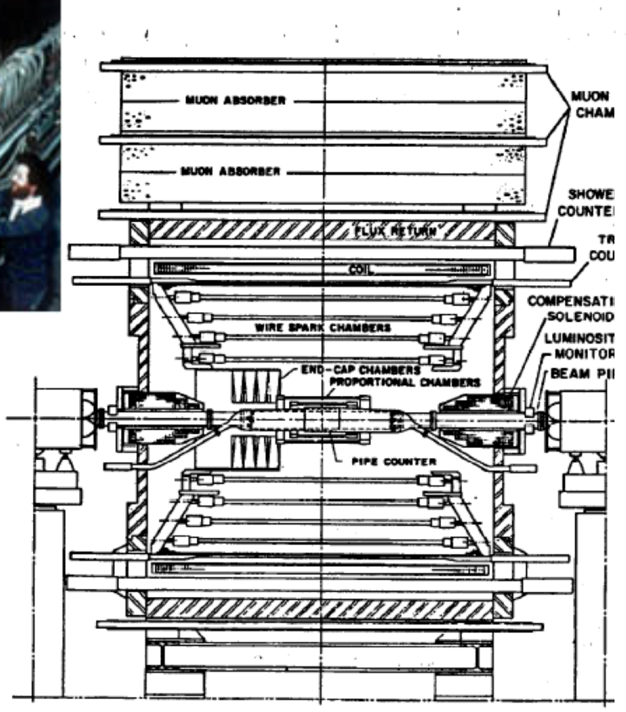
Mark I detector

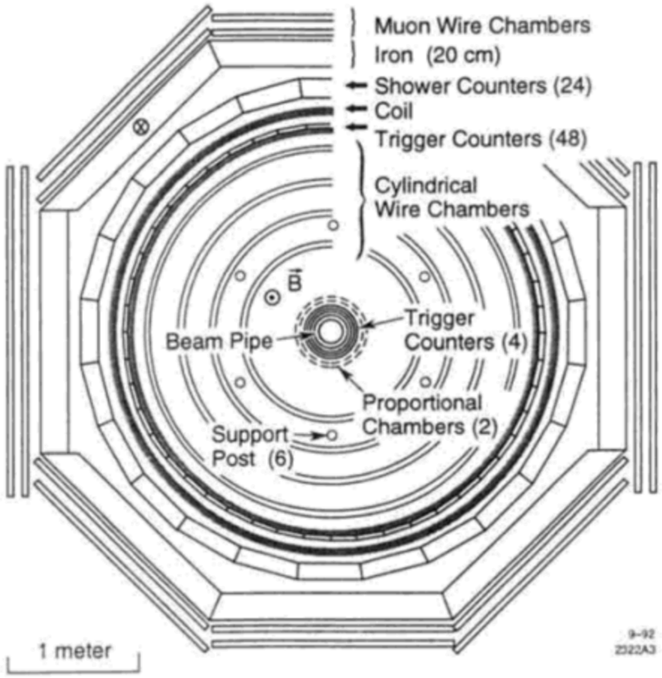
Mark I @ SPEAR (SLAC), 1973



Mark I or the SLAC-LBL Magnetic Detector was the first 4π detector built with different detector types arranged in layers around the interaction point. Had the known sensors at the moment:

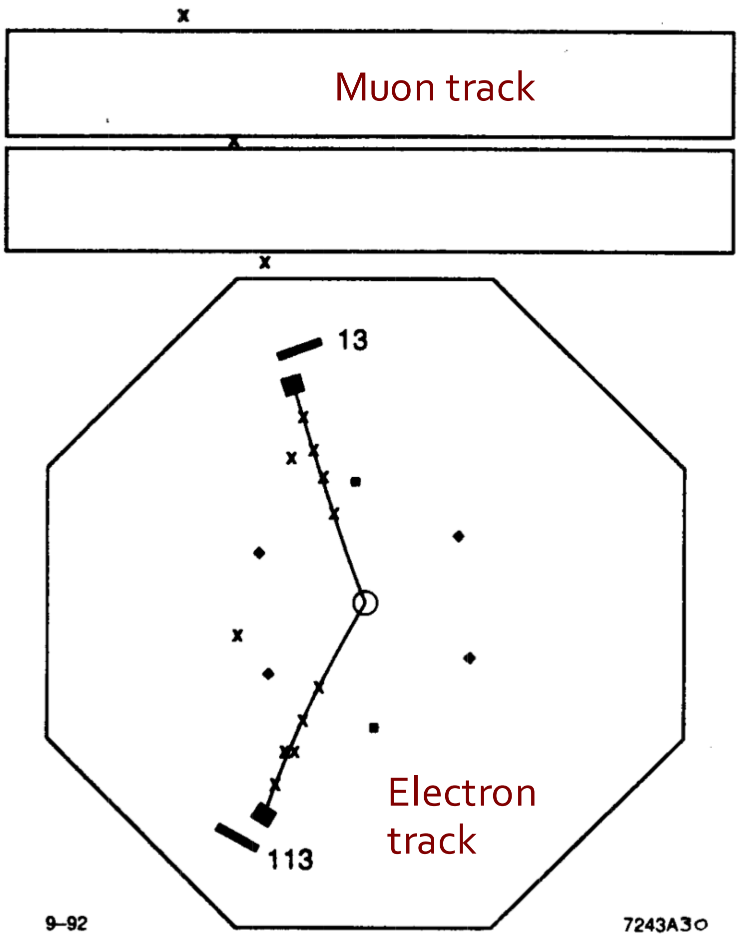
- Wire chambers and
- “Shower Counters” or calorimeters



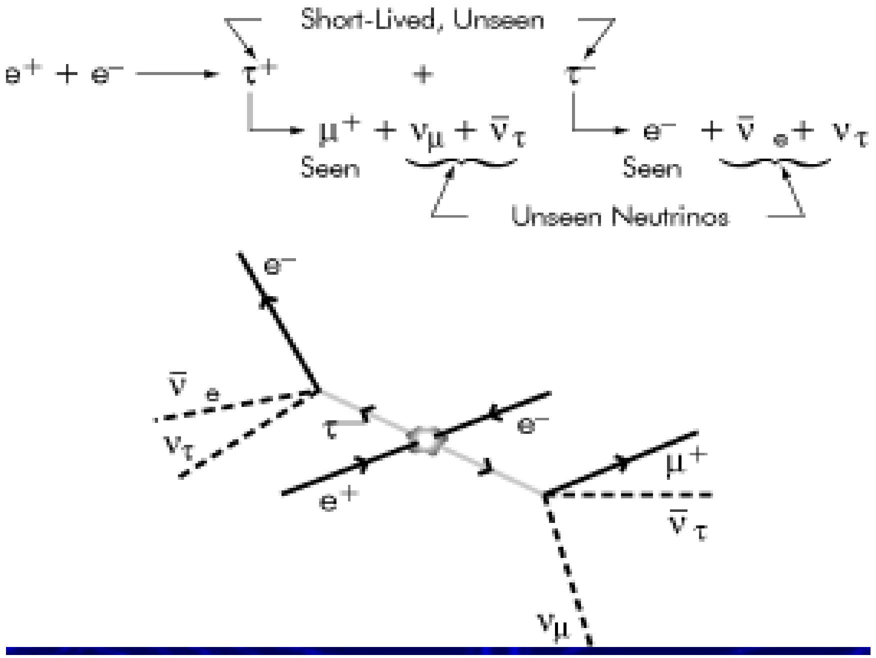


Mark I detector: The tau lepton

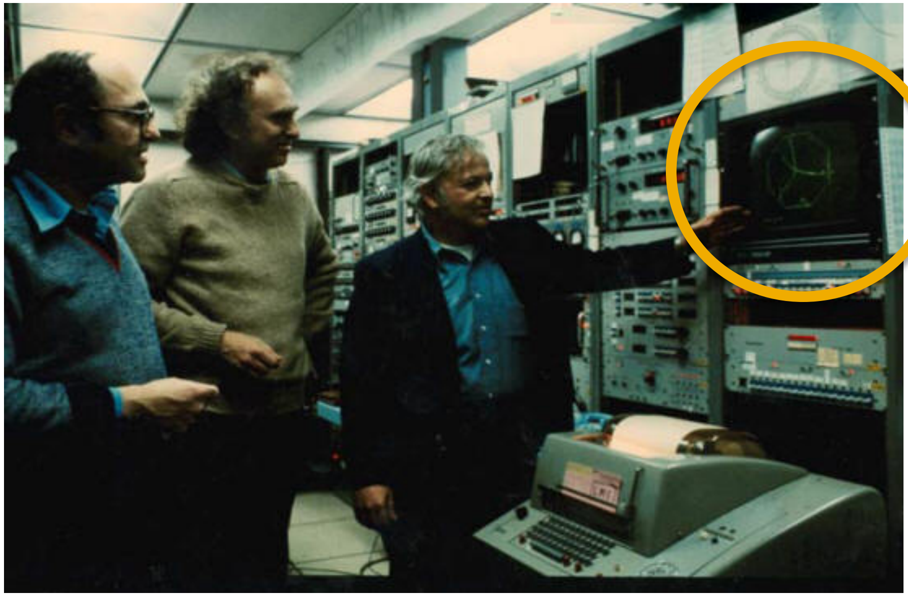
The e-μ events seen at Mark I

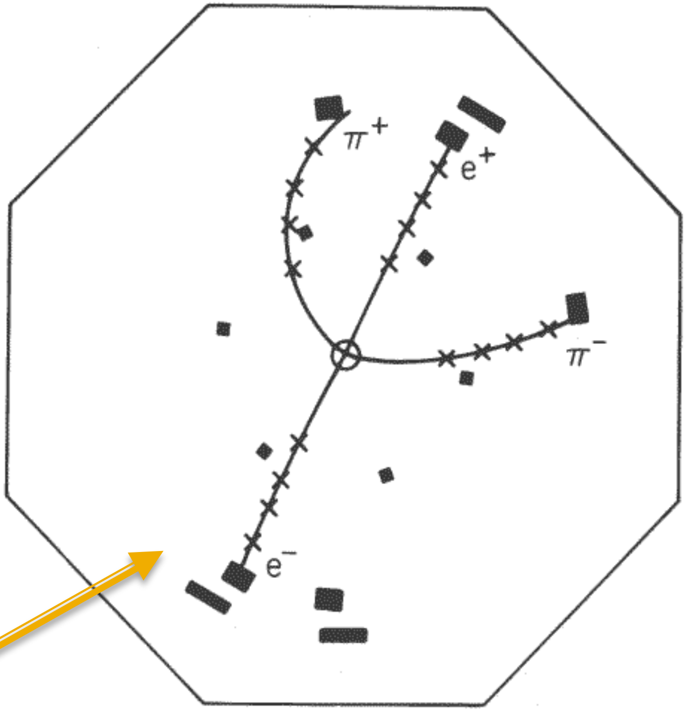


M. Pearl, 1975

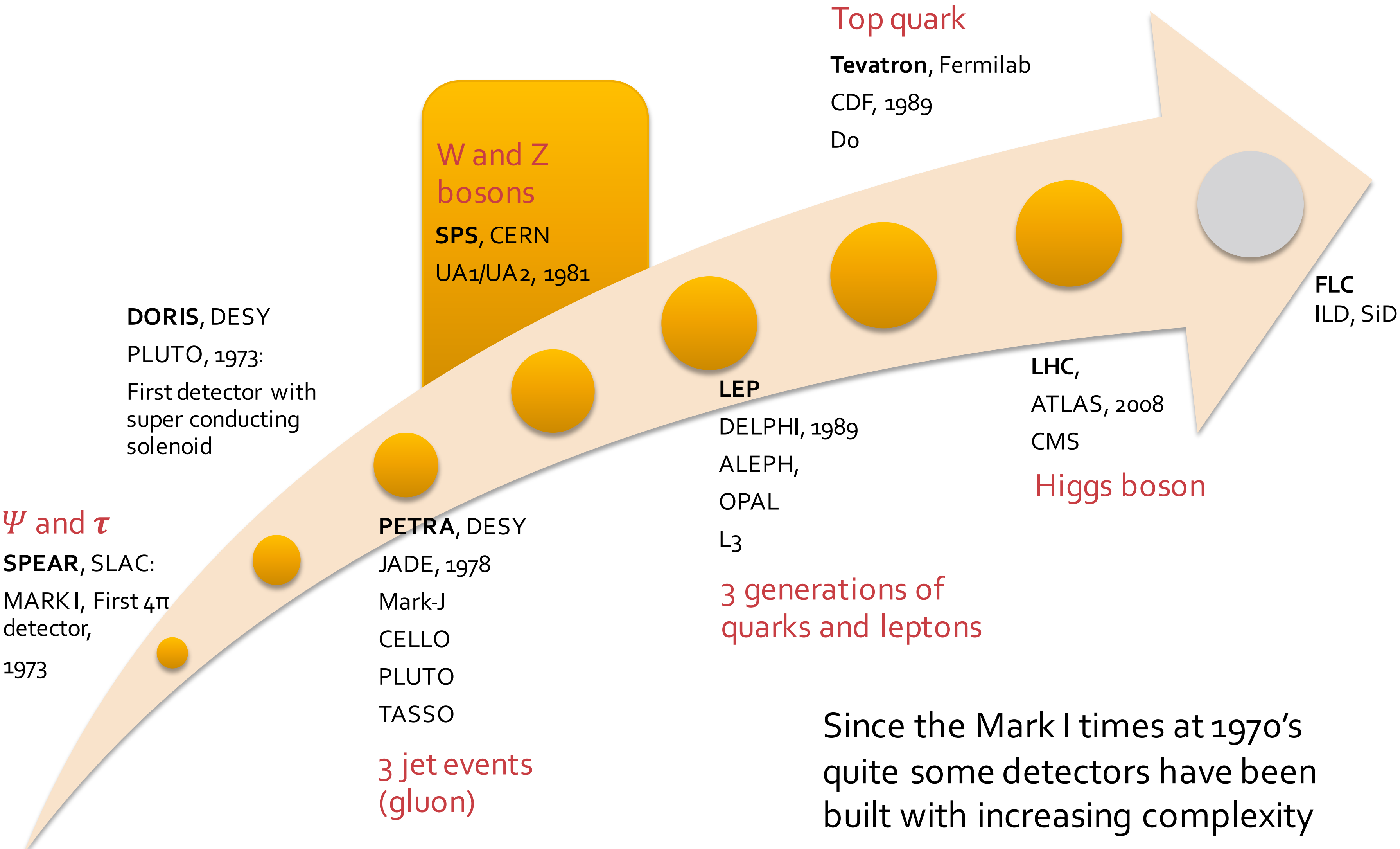


Mark I: The Psi resonance



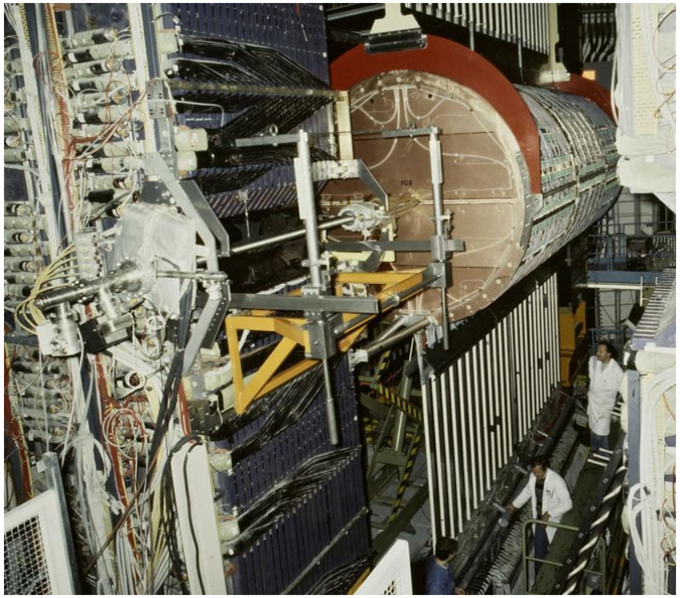


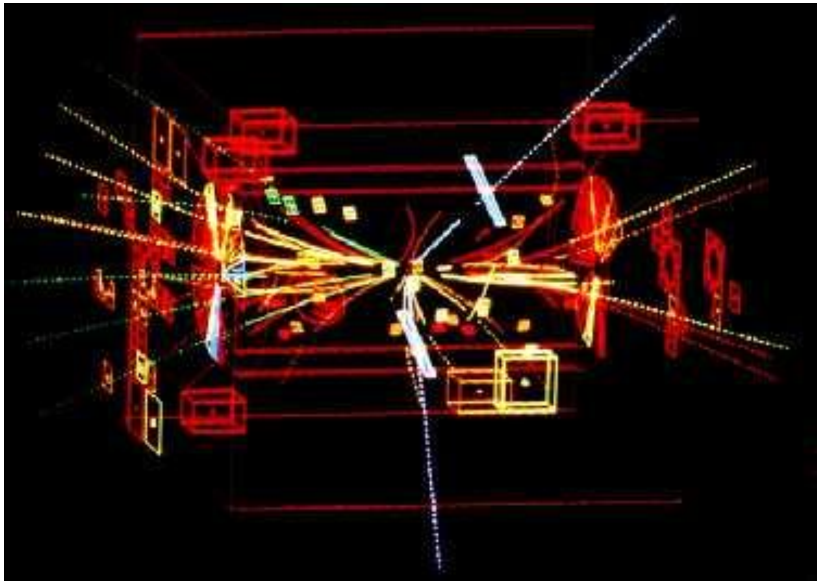
Particle detectors for colliders



Since the Mark I times at 1970's quite some detectors have been built with increasing complexity

UA1: the W and Z discovery





UA1 was a multipurpose detector.

The central detector of UA1 was a six-chambered cylinder, 5.8 metres long and 2.3 metres in diameter. It was the largest imaging drift chamber of its day.

UA1 recorded the tracks of charged particles curving in a 0.7 Tesla magnetic field, measuring

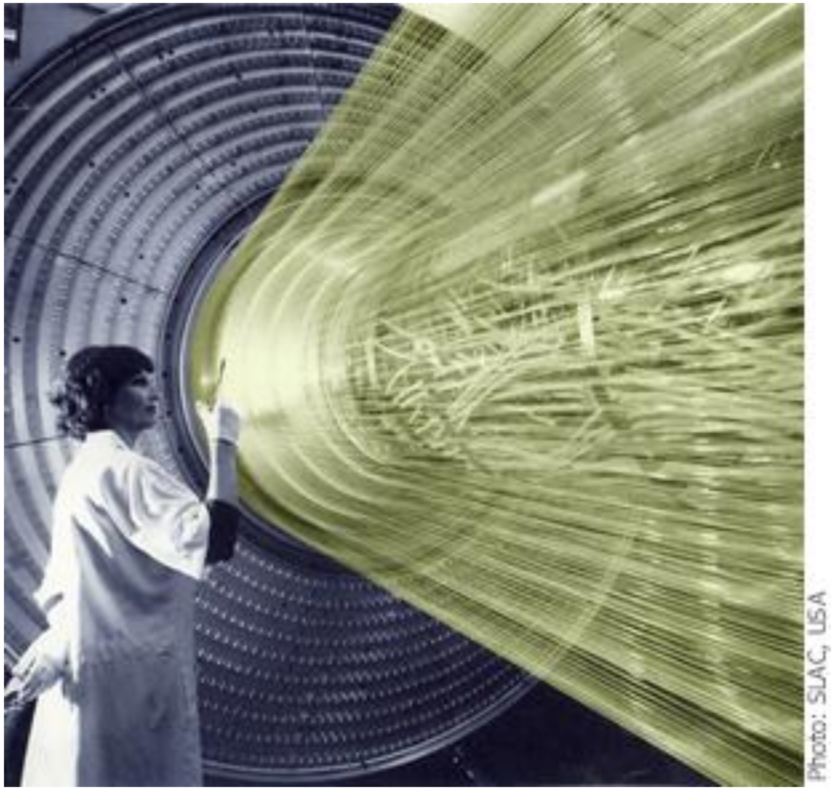
- their momentum,
- the sign of their electric charge and
- their rate of energy loss.

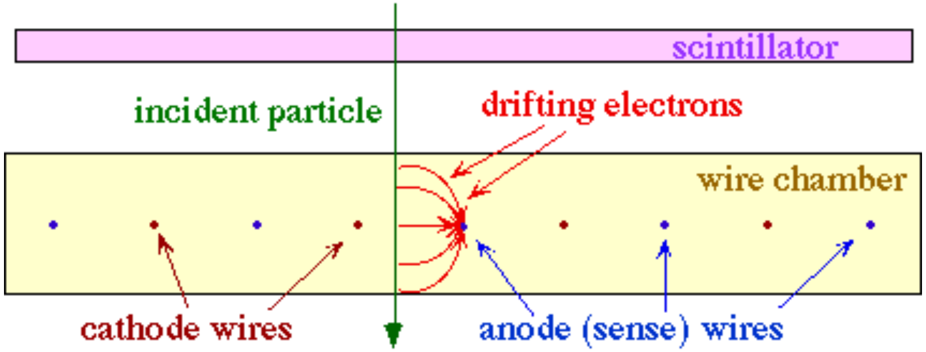
Outside the magnet were the calorimeters: one hadronic and another electromagnetic.

Surrounding the detector, the muon chambers

Drift Chambers

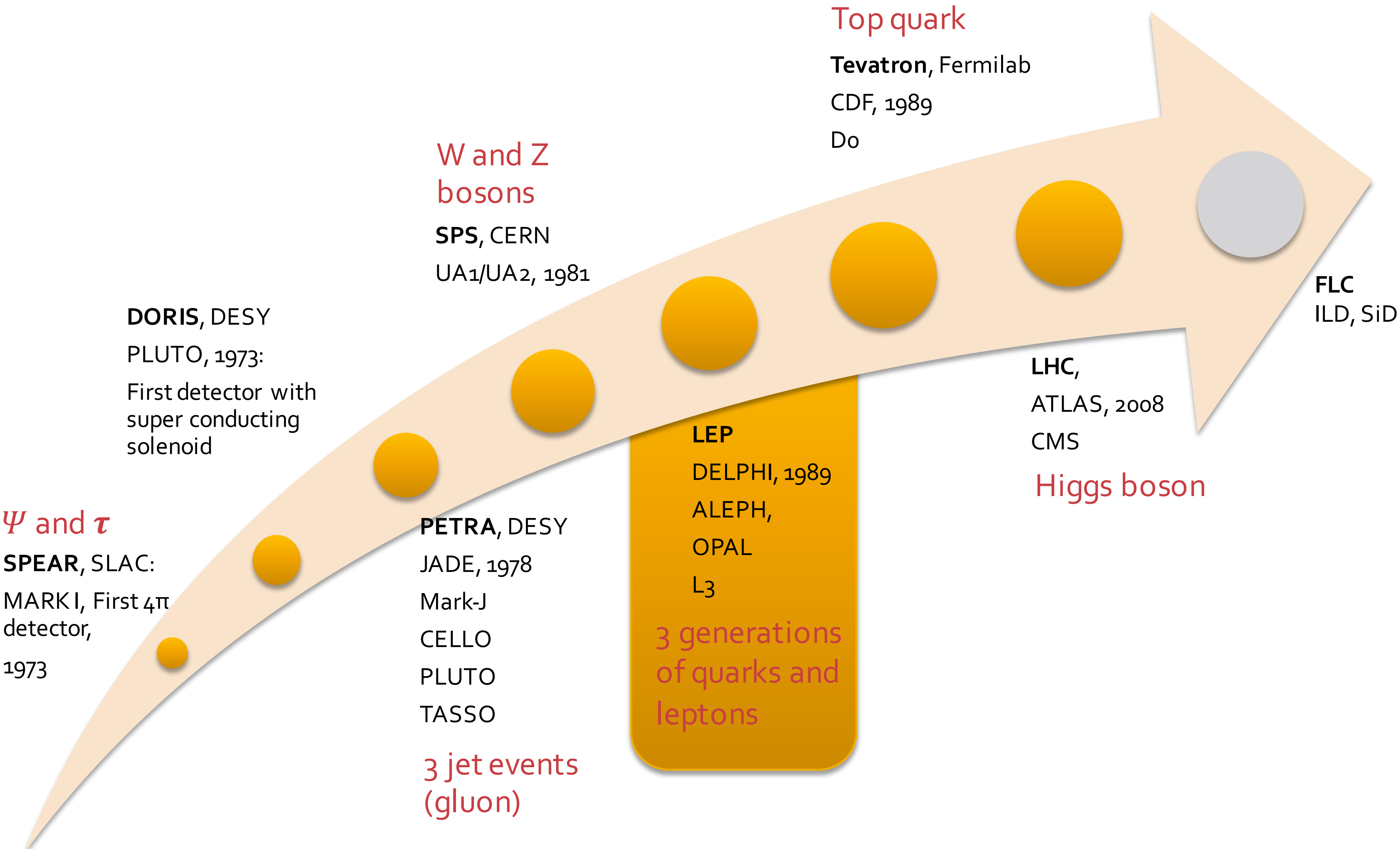
In the 1980's most of the tracking in Collider detectors is made with Drift Chambers. They allowed to recover the "image" that Bubble chambers had provided until the end of the 1960's





Measuring this drift time, i.e. the time between passage of the particle and the arrival time of the electrons at the wires, made this detector a precision positioning device.

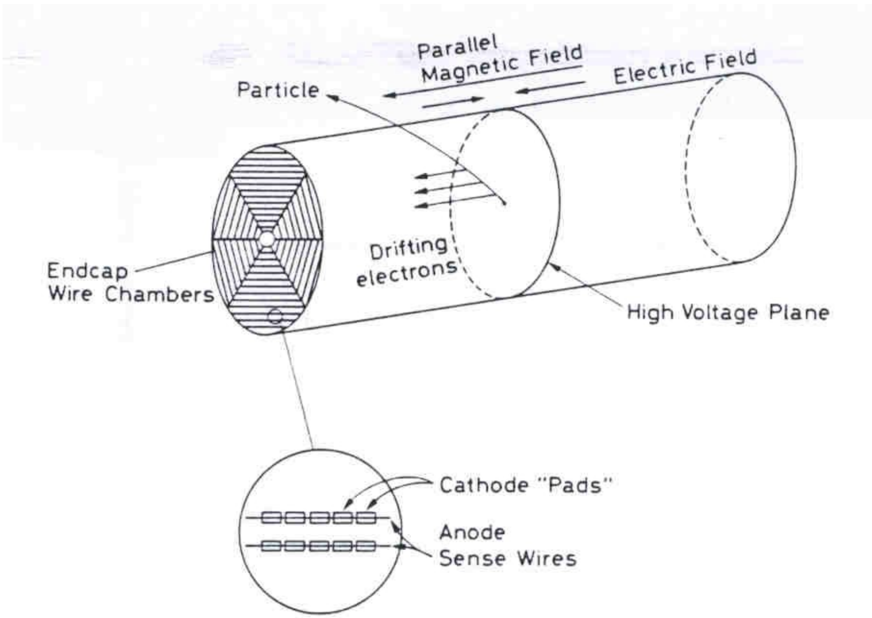
Particle detectors for colliders



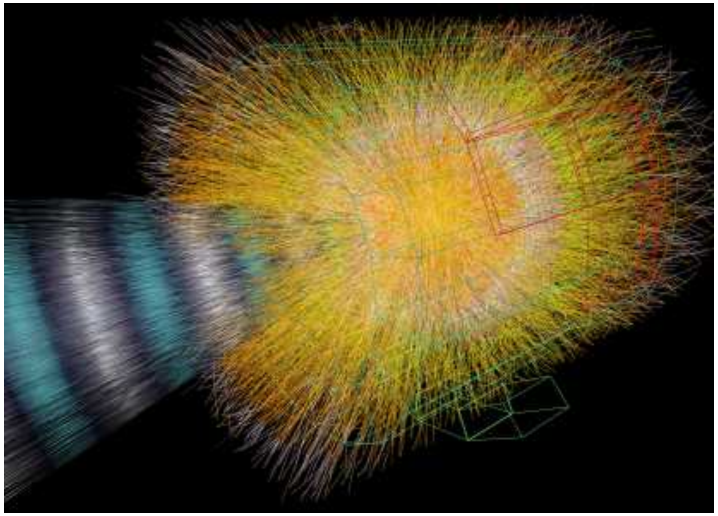
LEP detectors

- LEP was a Z and W factory and dreamed about finding the Higgs.
  - They claimed to have hints of a 115 GeV/c^2 Higgs.
- Detectors at LEP introduced some new concepts that helped performing much better than expected:
  - Time Projection Chamber (TPC)
  - Ring Imaging Cherenkov (RICH)
  - Silicon Vertex Detectors for "vertexing"

Time Projection Chambers



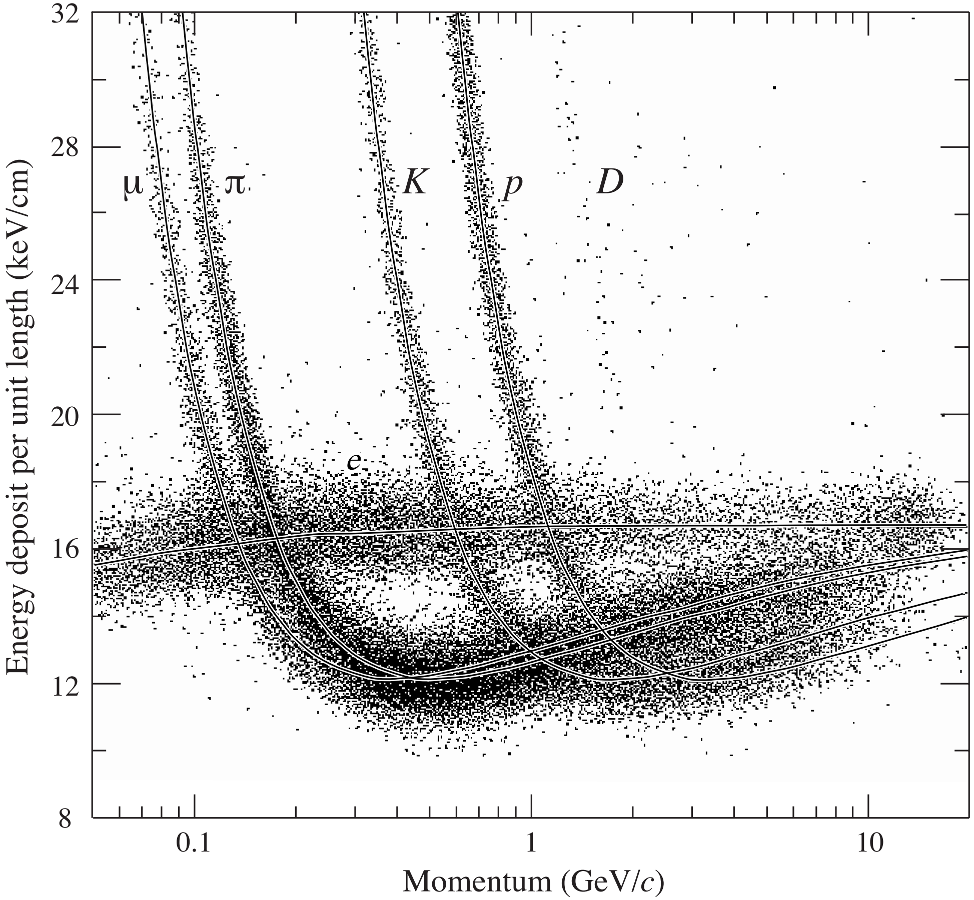
The Time Projection Chamber was introduced in 1976 **by D.R. Nygren**



A volume filled with gas in an electric field. When the particle traverses the volume, ions drift to the cathode and electrons to the anode which is segmented.

From the drift time one determines Z, from the endplate segments one determines X and Y. We have a 3D reconstruction of the particle trajectory.

Time Projection Chambers



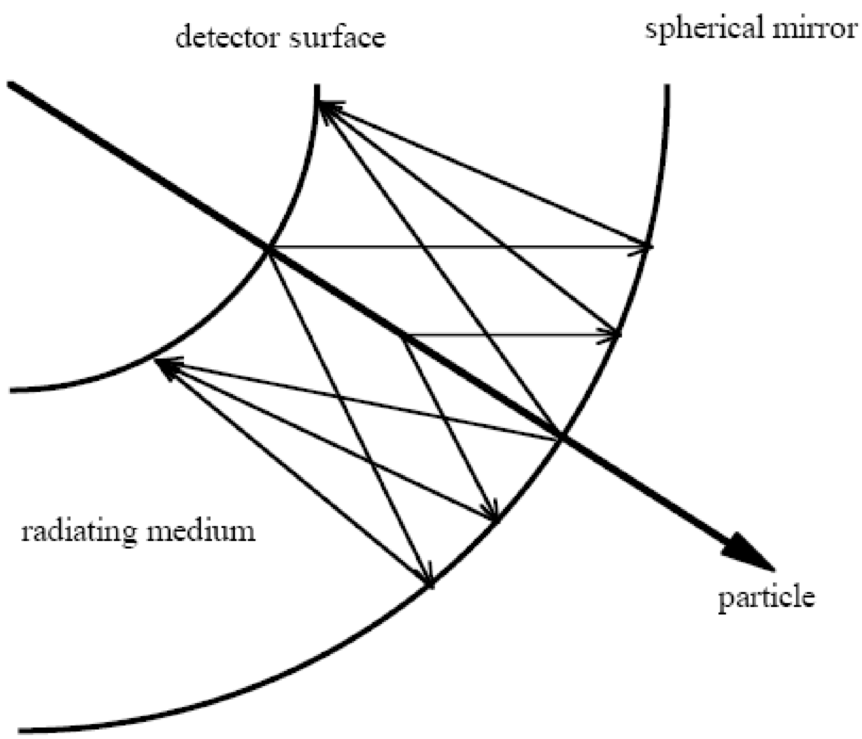
PEP4/9-TPC energy-deposit measurements

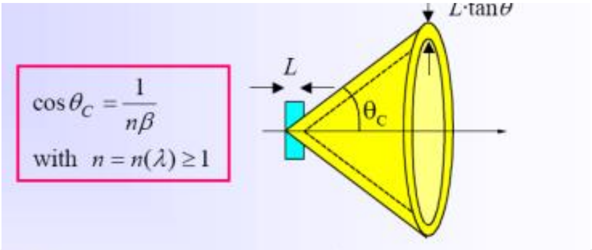
The TPC provides particle identification by dE/dx

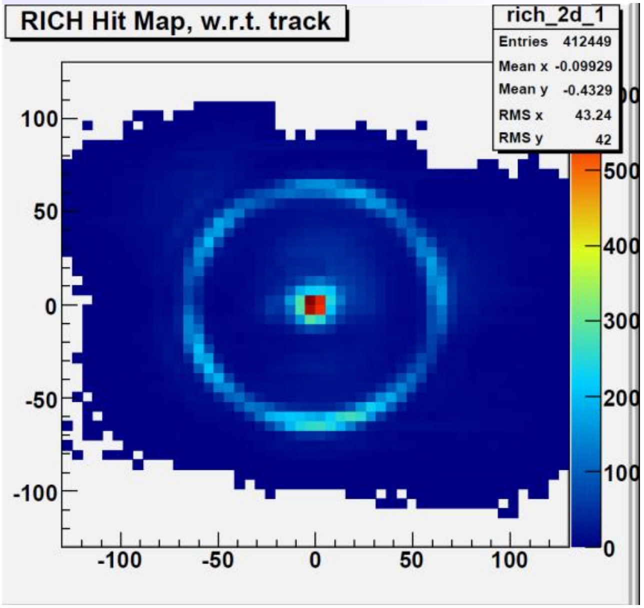
Ring Imaging Cerenkov (RICH) Detectors

Proposed by J. Seginot and T. Ypsilantins in 1977.

Project the Cerenkov light back into a detector where we can reconstruct the circles of the Cerenkov light cone traversing the detector.
For a known momentum (from curvature in a magnetic field) **we can determine the mass** by measuring the speed..







Silicon detectors

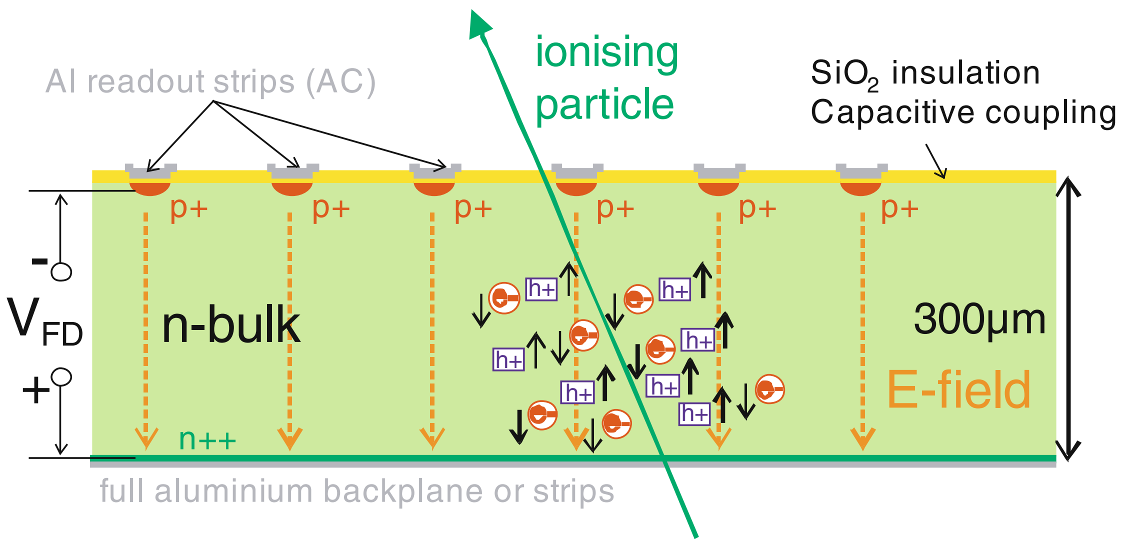
The working principle of silicon detectors is like the gaseous detectors.

We have a volume where ionization produces charge carriers that drift under the effect of an electric field. While moving they induce electric currents that we can measure.

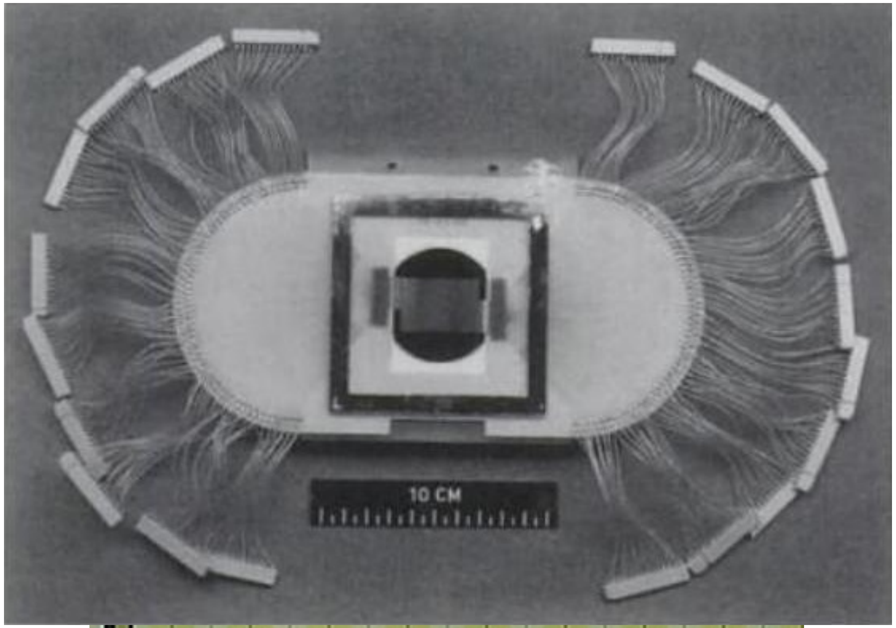
The sensitive volume is the depletion region of a reverse biased pn-junction.

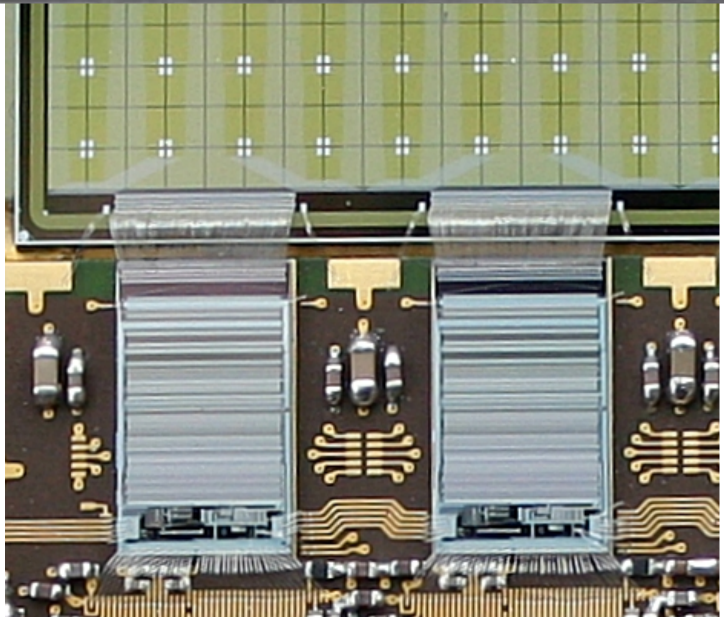
It sounds like electronics, and it is indeed profiting from almost electronics industry standards.

PN-junctions can be made with strips (1D information) or pixels (2D information)



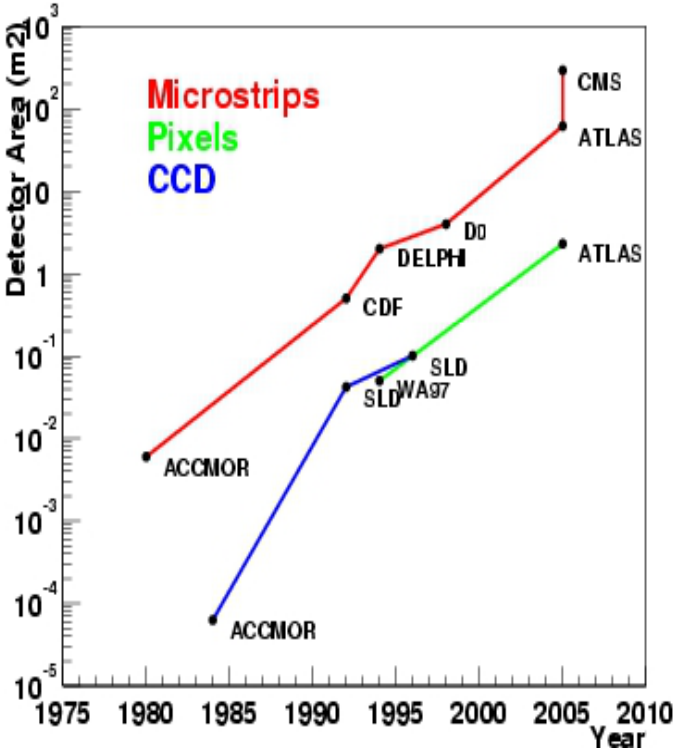
Silicon detectors





Silicon detectors.
In the early 1980s silicon sensors appeared in the game.

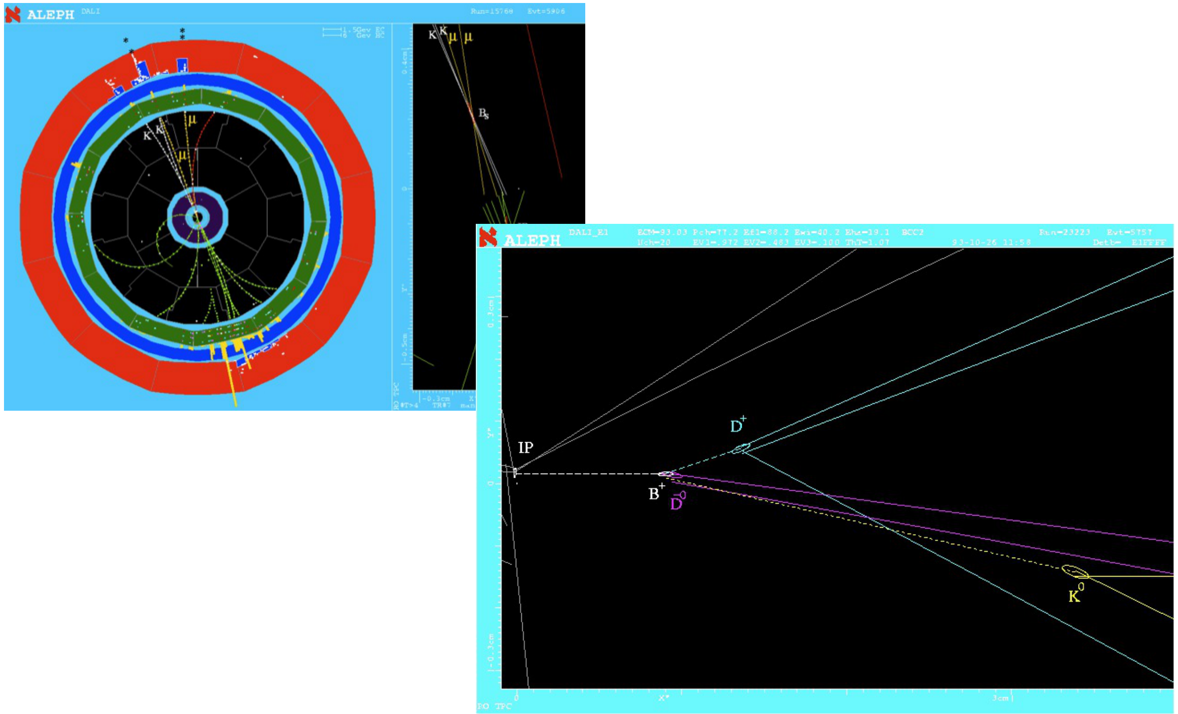
The increasing number of channels and how to connect the detector to the readout electronics soon starts to be an issue.



Why silicon detectors where so important ?

Quark tagging and spectroscopy of short-lived particles demanded high precision tracking with flavour tagging possibilities by identifying secondary decay vertices.

Lifetimes of the order of 0.2-1.5 ps required spatial resolutions better than a few μm



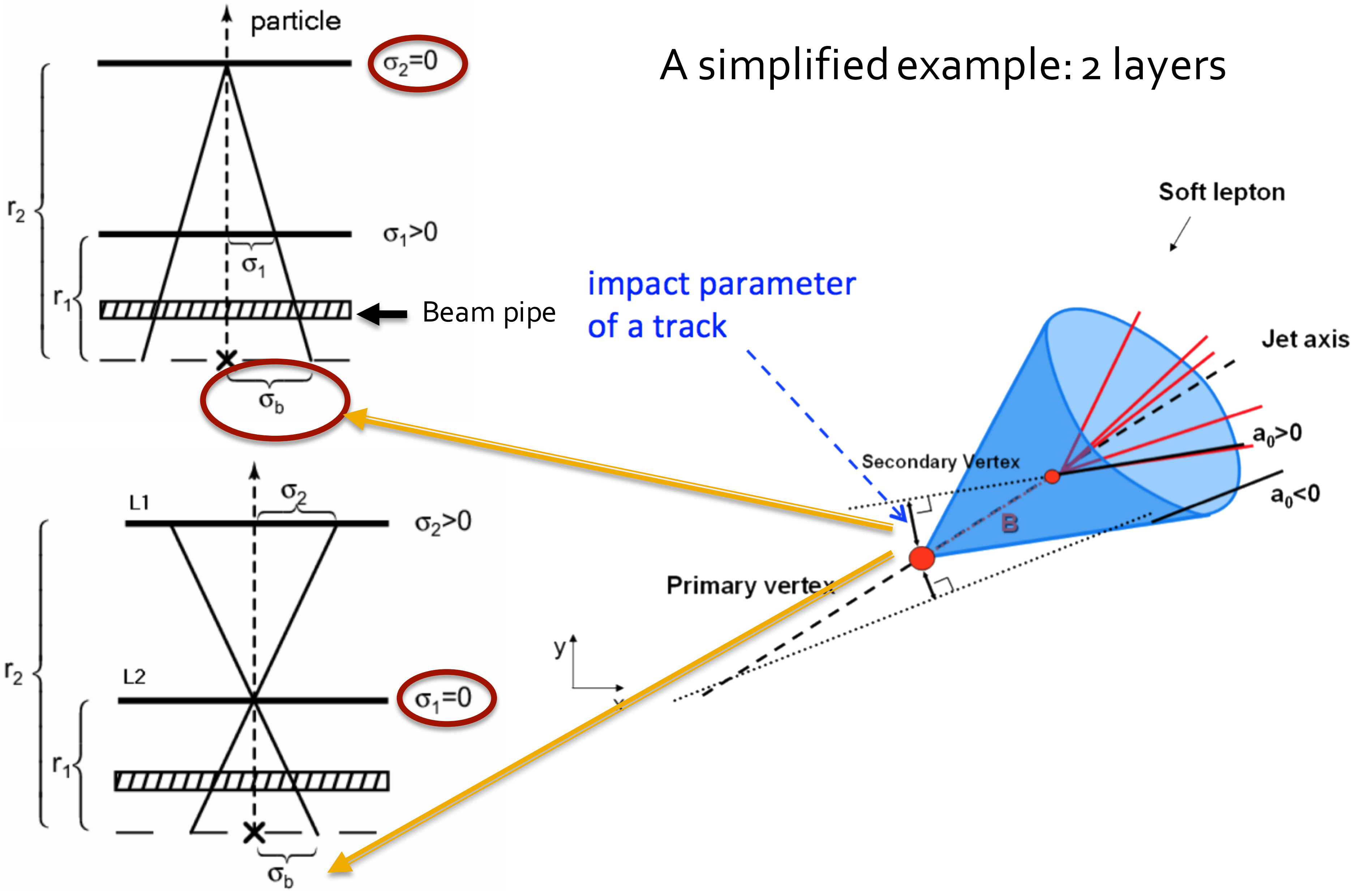
The life time of B-mesons can be measured from the decay length l, if the momentum of the B-meson (γ-factor) is measured as well.

The resolution of the "vertex detectors"

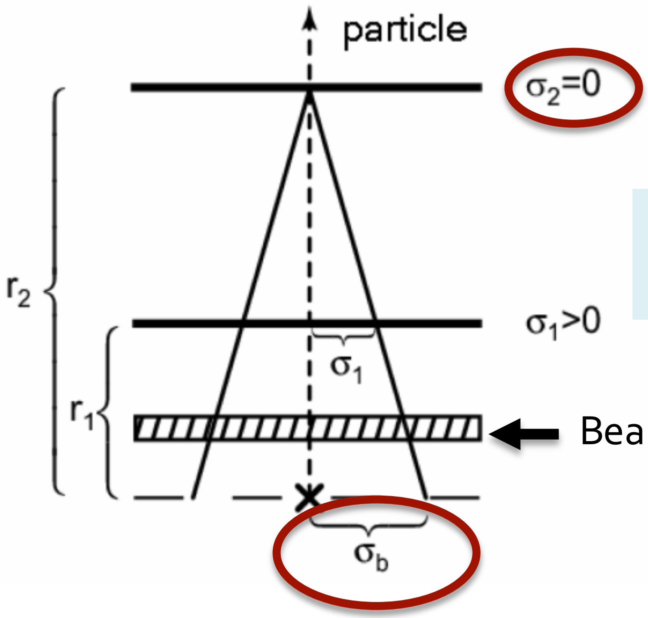
- Resolution has three main components
  - Intrinsic resolution of the detectors
  - Geometry and,
  - Multiple scattering ("material budget")

The resolution of the "vertex detectors"

A simplified example: 2 layers



The resolution of the "vertex detectors"



A simplified example: 2 layers

$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

Small !!

Small !!

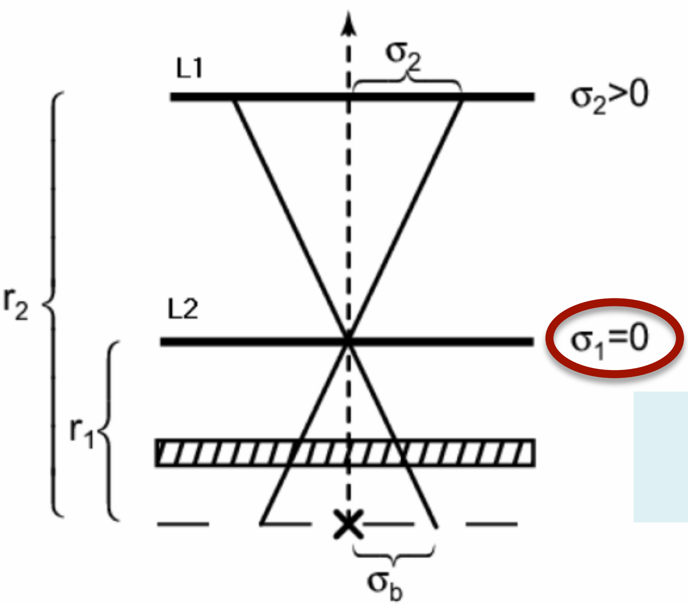
Multiple scattering

$$\sigma = \left(\frac{r_1}{r_2 - r_1}\sigma_2\right)^2 + \left(\frac{r_2}{r_2 - r_1}\sigma_1\right)^2 + \sigma^2{}_{MS}$$

Sort of large

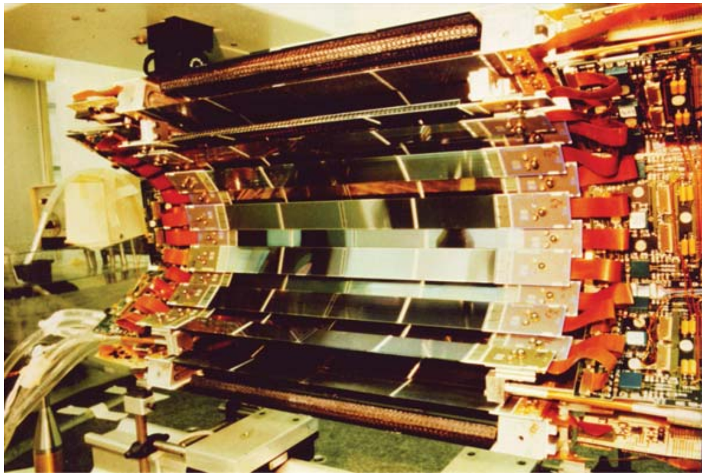
Small x/X_0!!

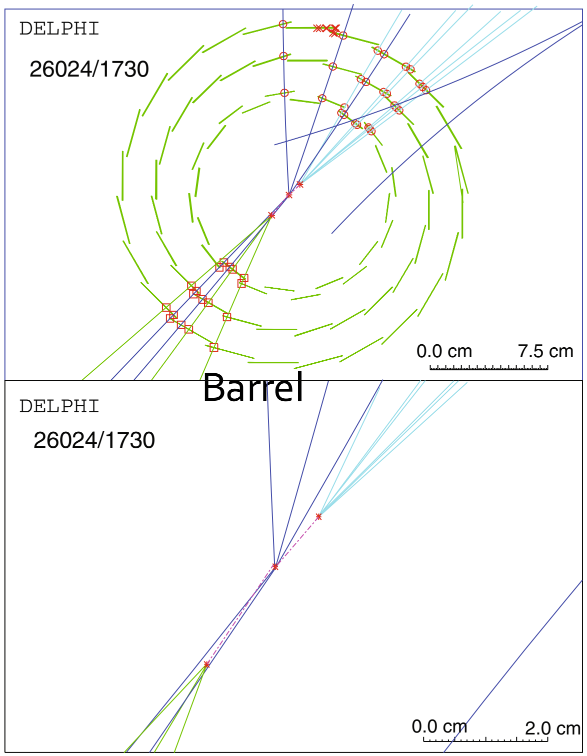
$$\sigma_{MS} \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

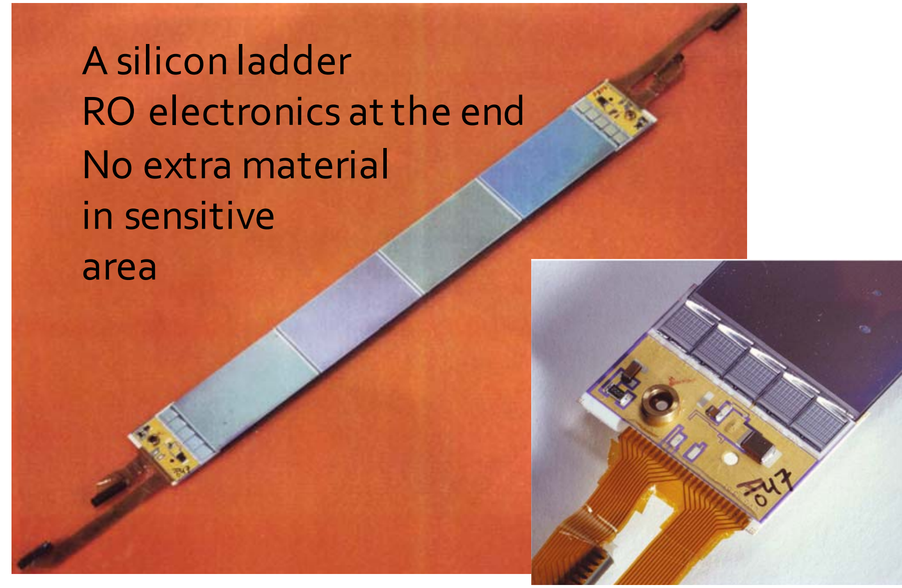


$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

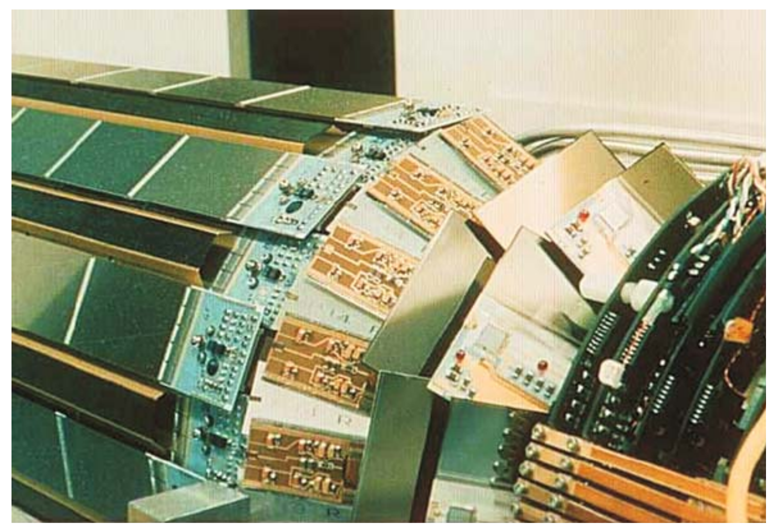
DELPHI micro-vertex



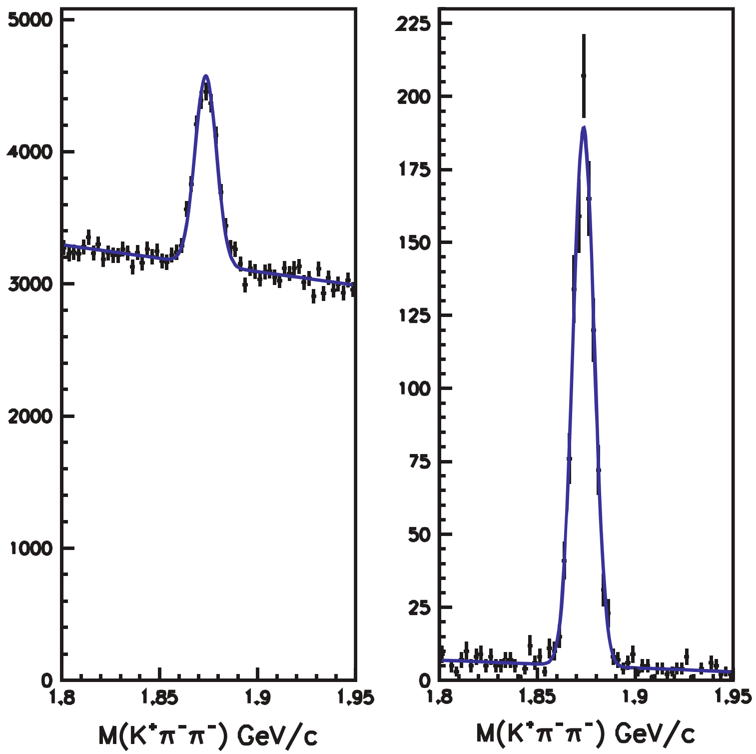


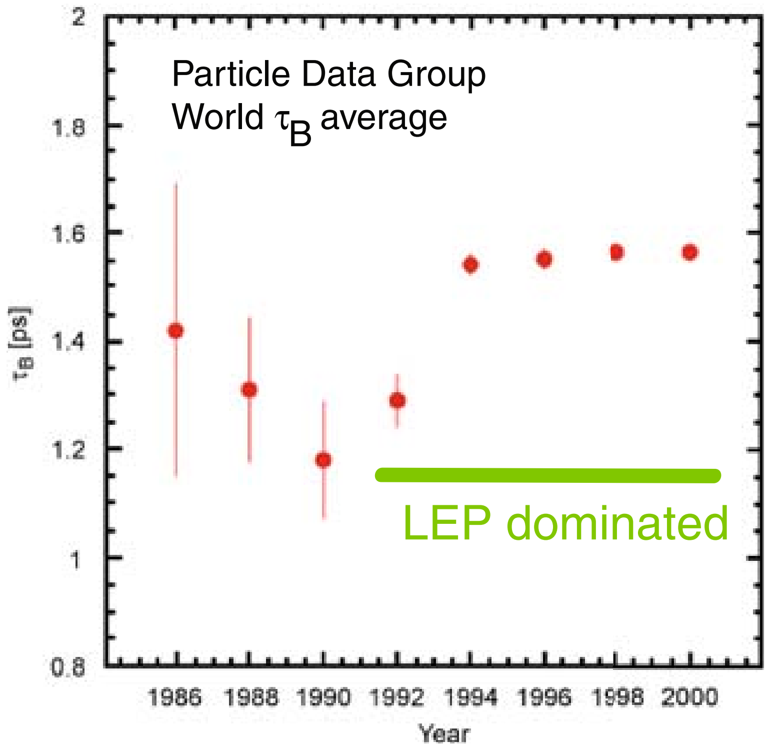


The very forward part



Physics improvements

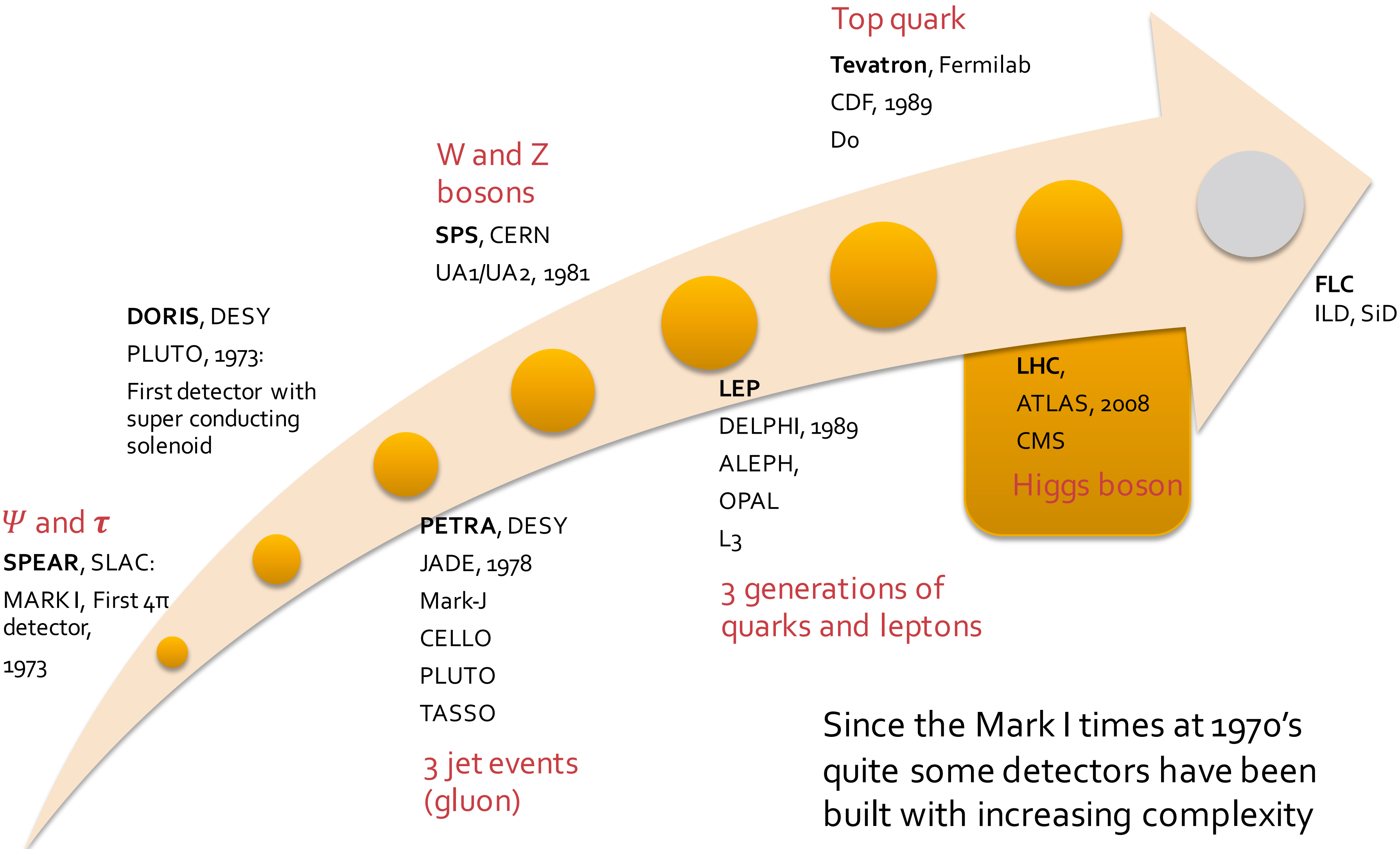




$D^{\pm} \rightarrow K\pi\pi$ peak without (left) and with Vertex detector cut removing background.

B lifetime in time.
Guess when the silicon detectors started in LEP…

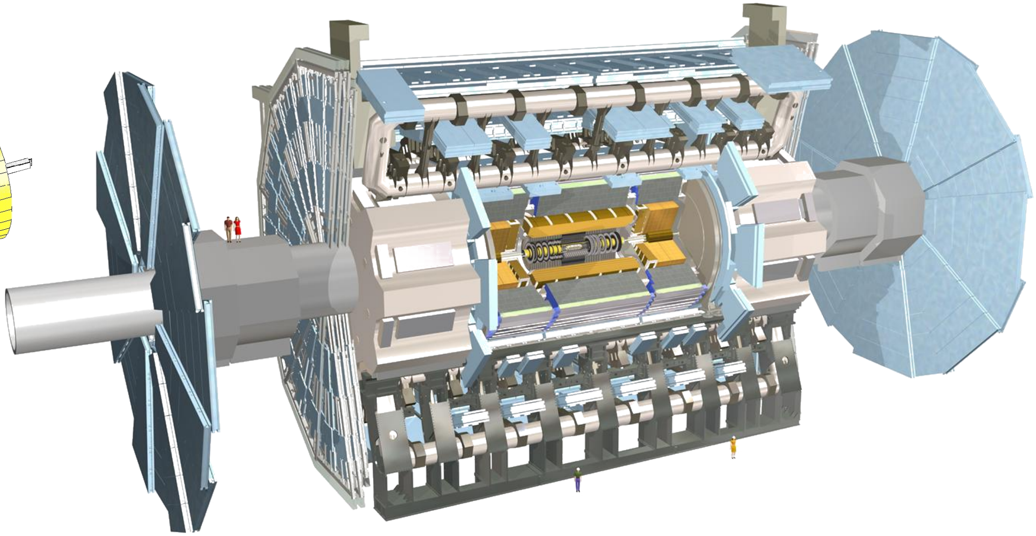
Particle detectors for colliders



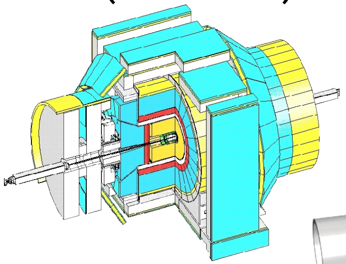
Since the Mark I times at 1970's quite some detectors have been built with increasing complexity

Particle Detectors for colliders

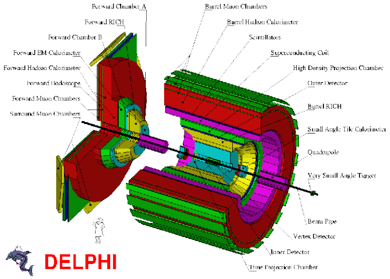
ATLAS (25x45 m)



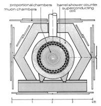
CDF (12x12 m)

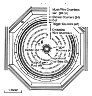


DELPHI (10x10)m



PLUTO (4x4 m)



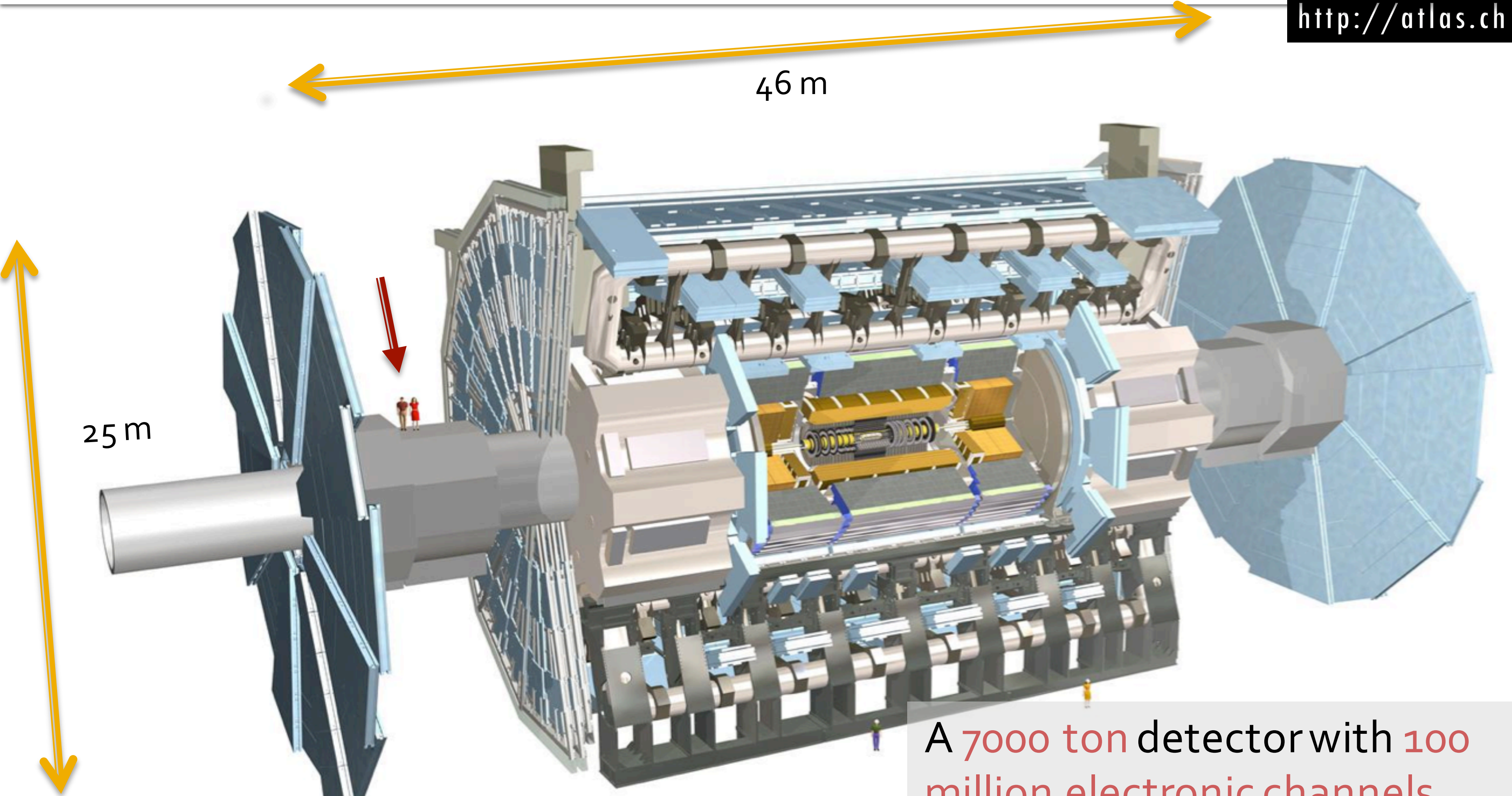


Mark I (4x4 m)

Volume of both detectors and collaborations have grown considerably.

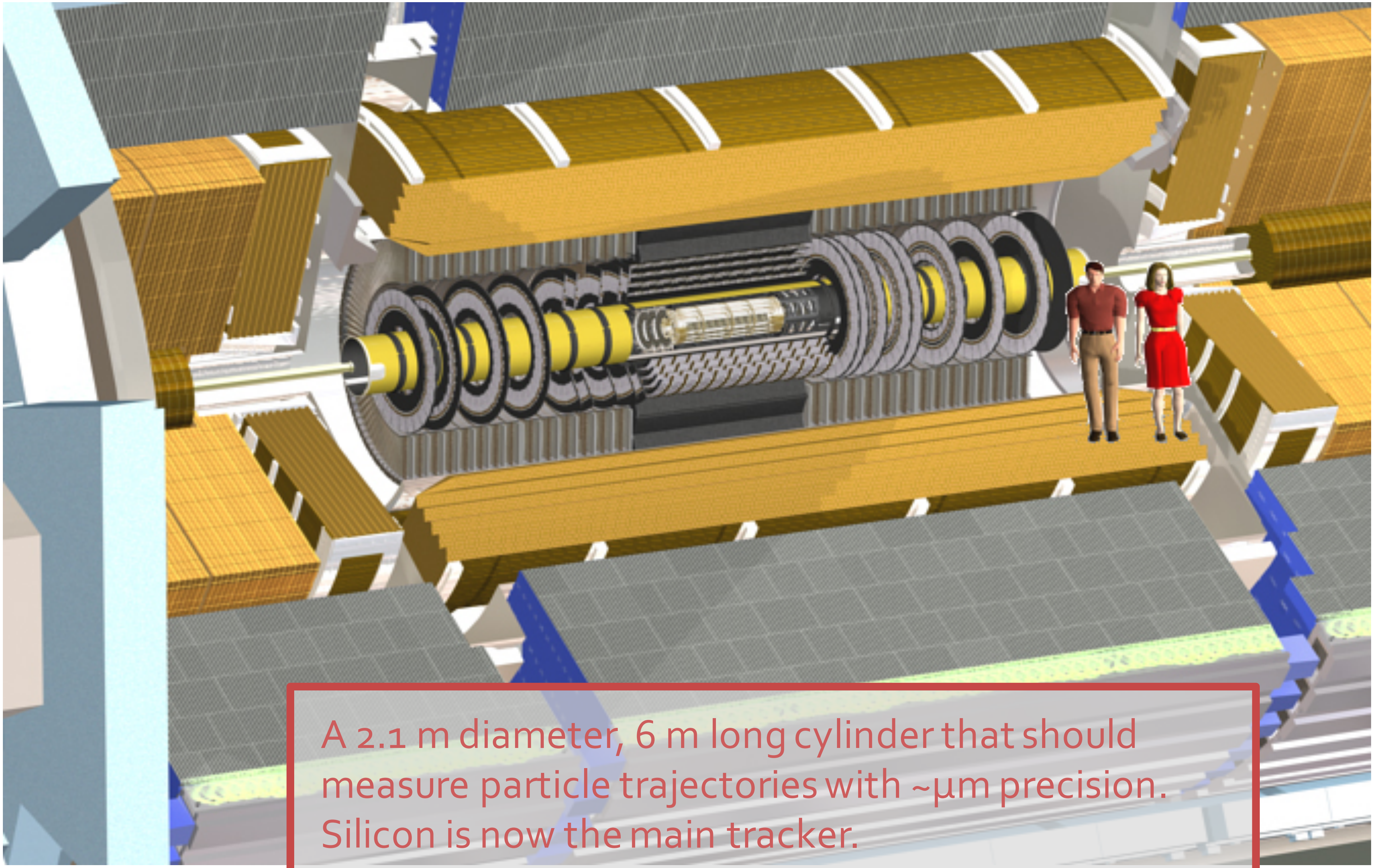
The working model has also changed dramatically

LHC era: 2 order of magnitude larger



A 7000 ton detector with 100 million electronic channels and 3000 km of cables that could eventually float if a big enough bag could be found…

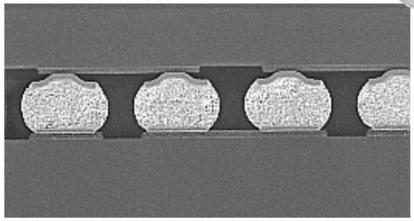
The ATLAS tracker

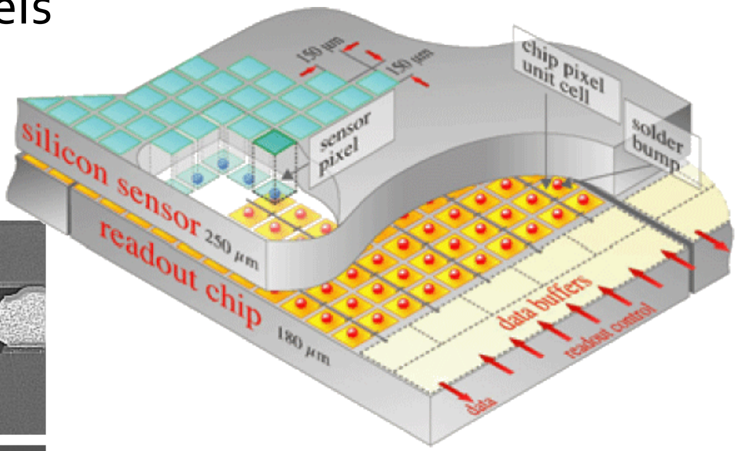


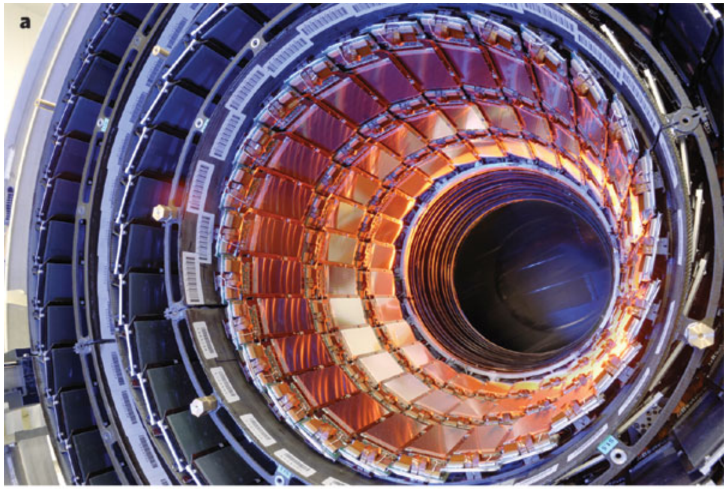
A 2.1 m diameter, 6 m long cylinder that should measure particle trajectories with ~µm precision.
Silicon is now the main tracker.

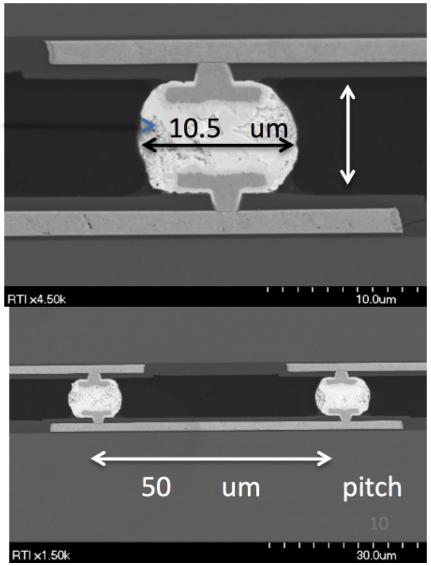
New pixel detectors

LEP used silicon strip sensors as vertex detectors and gas detectors as trackers. LHC uses silicon strip detectors as trackers and the new vertex detectors are made with pixels







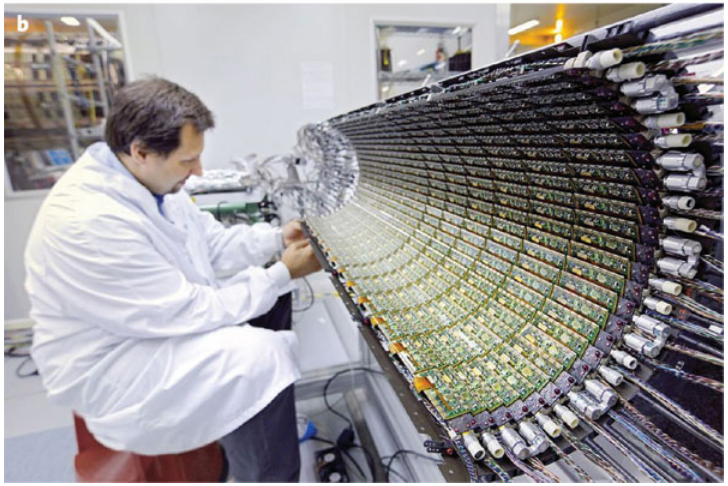


They provide almost 3D information in high rate environments like LHC.

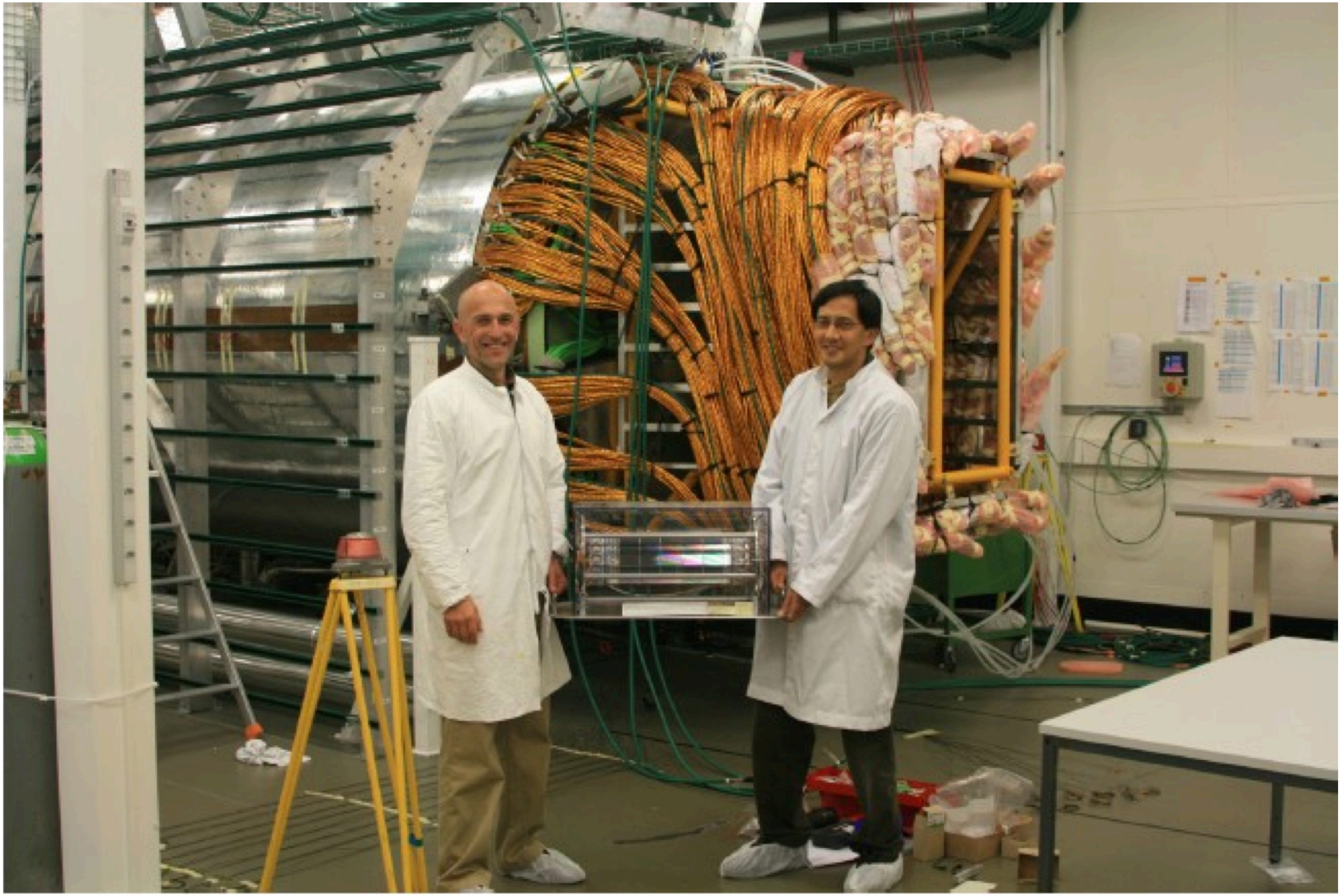
Very fine intrinsic resolution.

10000 channels/cm^2. Encapsulation

The amount of services is huge.

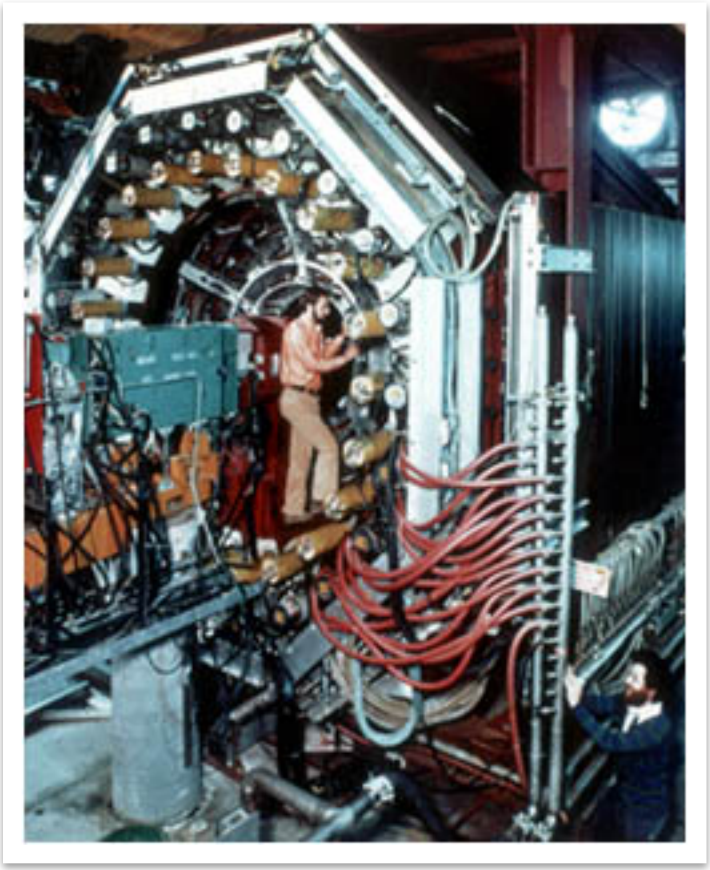


DELPHI microvertex – CMS Tracker



There is more than sensors in a Detector

There is more than sensors in a Detector



CHARGE PARTICLE TRACKING

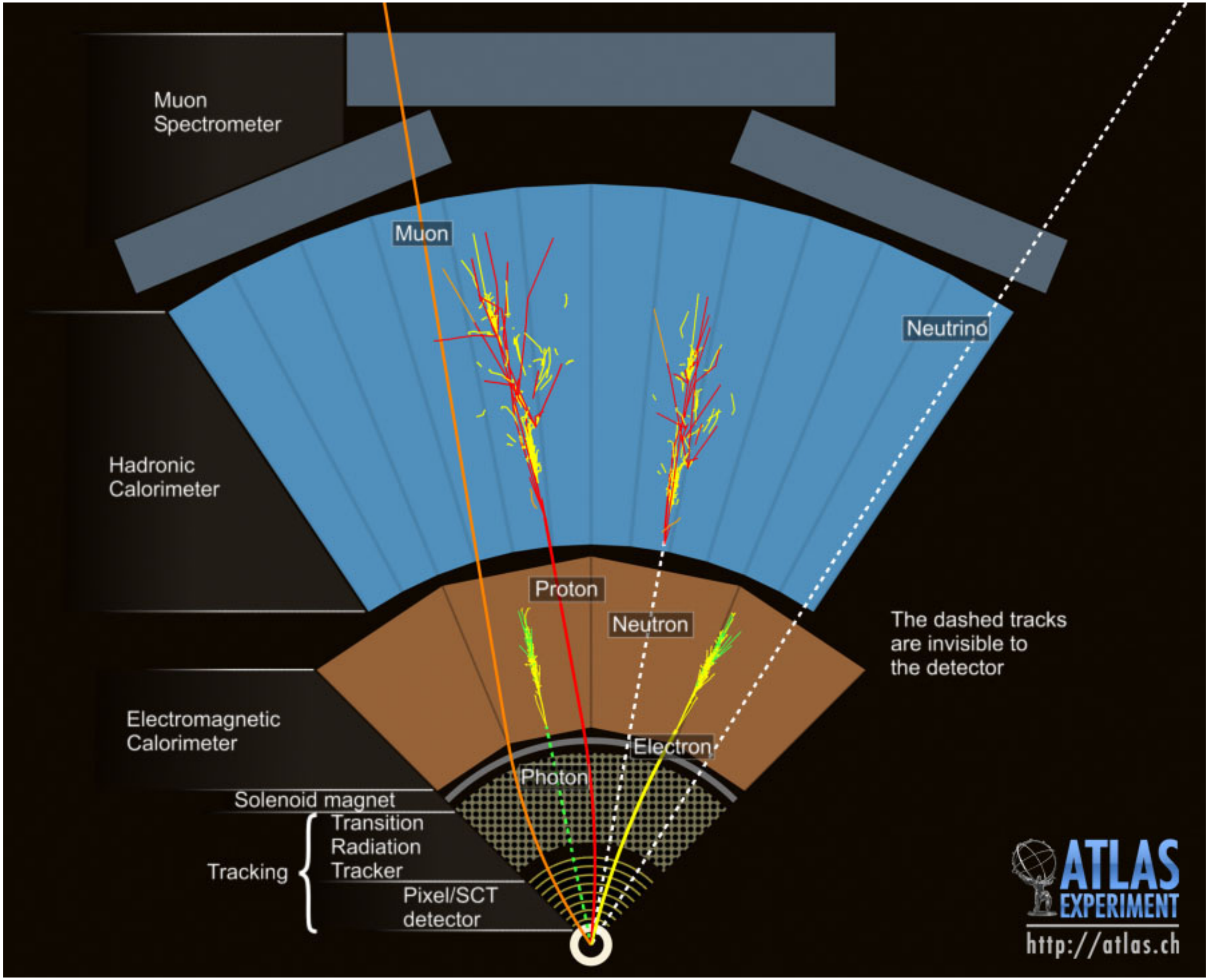
Particle Trackers

- All the interesting stuff happens within the first 10^{-12} seconds after the beams collide
  - We can only see “final state” particles
  - Our knowledge is based on “working backwards in time” to infer what actually happened in the initial collision
  - The more precisely the final state particles are measured, the more accurately we can determine the parameters of their parents.

A collider detector in a nutshell

Detectors at colliders aim at measuring

- the particle trajectory,
- charge,
- momentum,
- energy and
- do their best to figure out which particle it is…

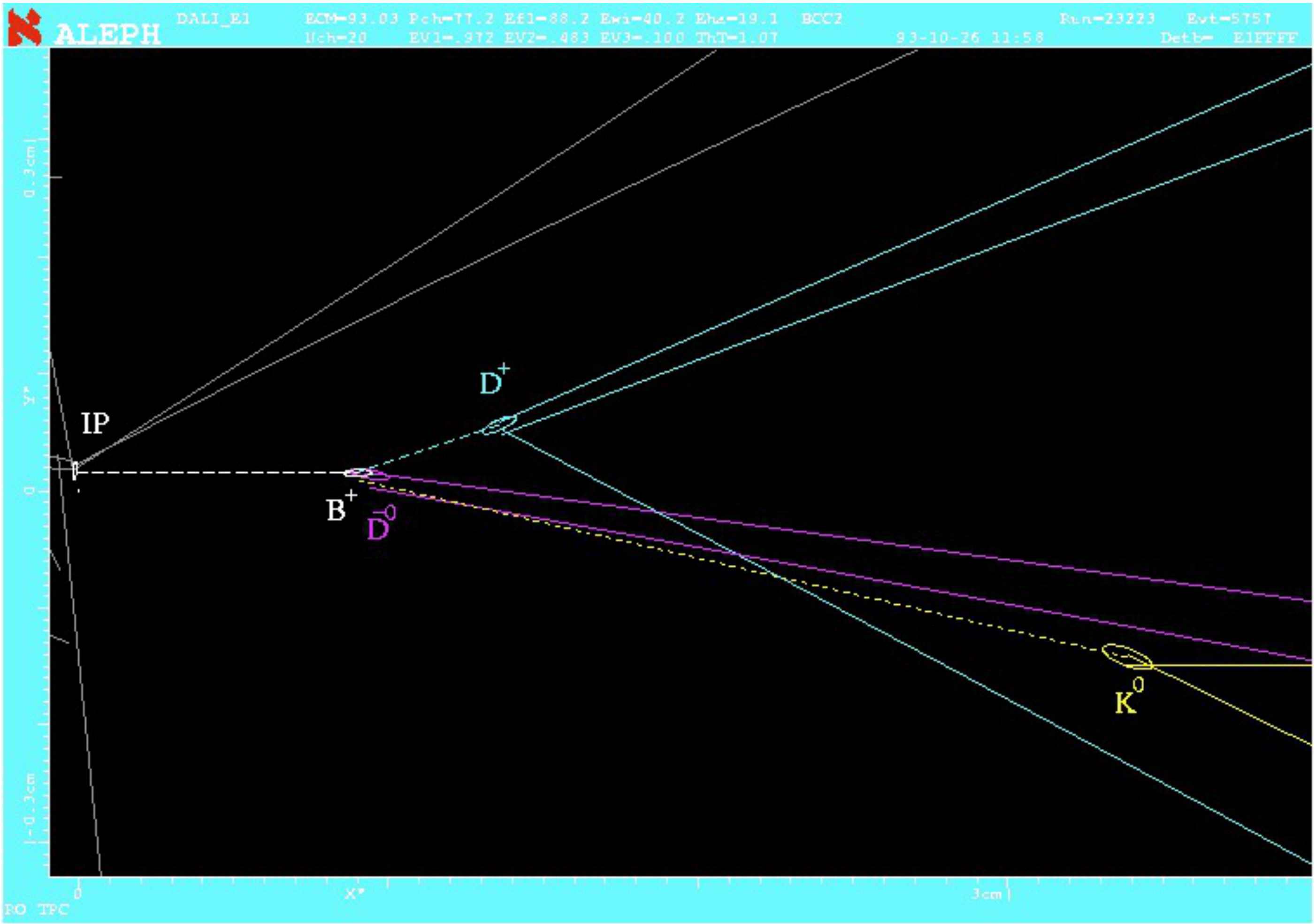


Why Tracking ?

- Tracking provides precise measurements of
  - Particle production position
    - Can reveal the presence of long-lived particles
  - Particle charge
  - Particle momenta
    - Complementary to calorimeter at low energy
  - dE/dx to help in the identification
  - Particle trajectories
    - Can associate information with calorimeters and muon chambers
      - Allows for "global pattern recognition" of physics objects

Why Tracking ?

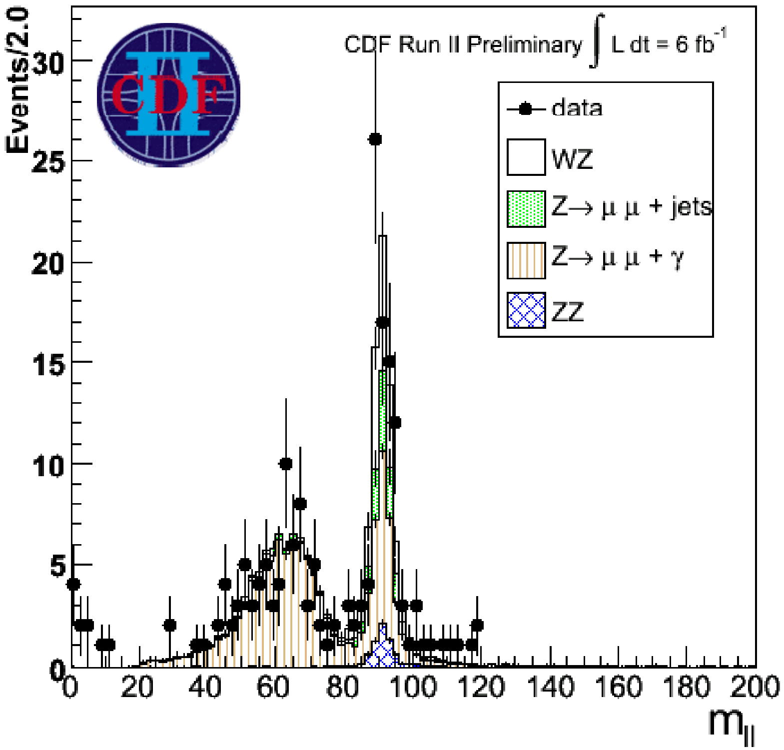
We can reconstruct disintegration chains



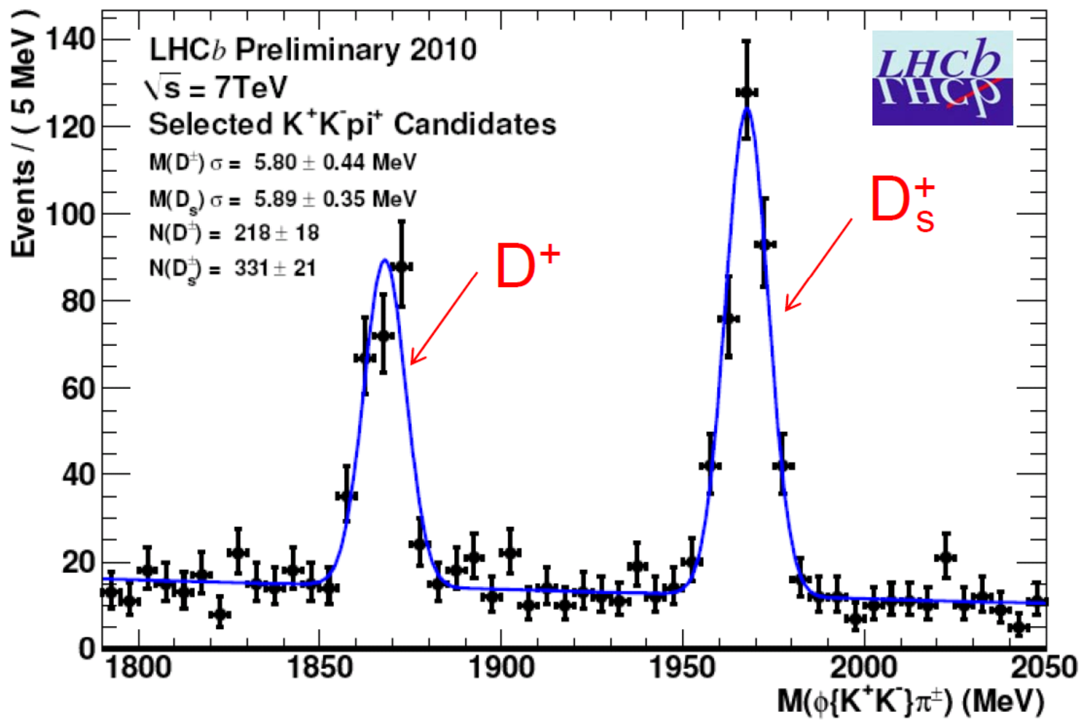
Why Tracking ?

We can accurately find resonances….

CDF: WZ and ZZ analysis

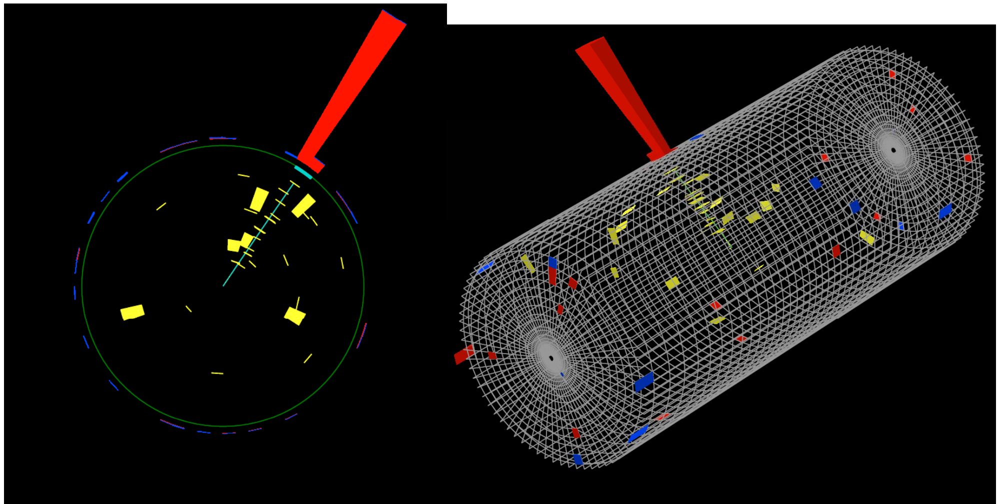


LHCb: exclusive charm reconstruction

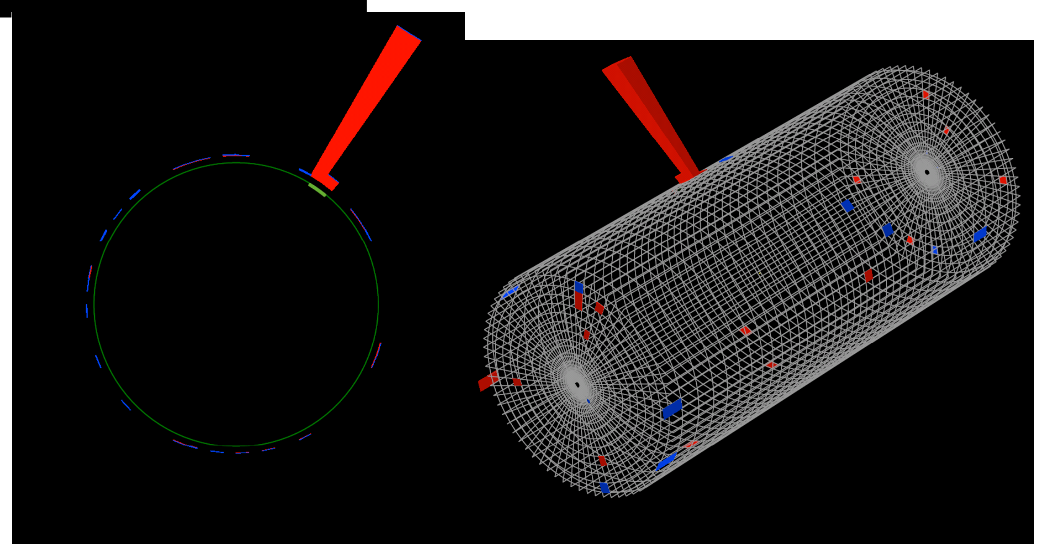


Why Tracking ?

We can differentiate an electron depositing EM energy on the calorimeter

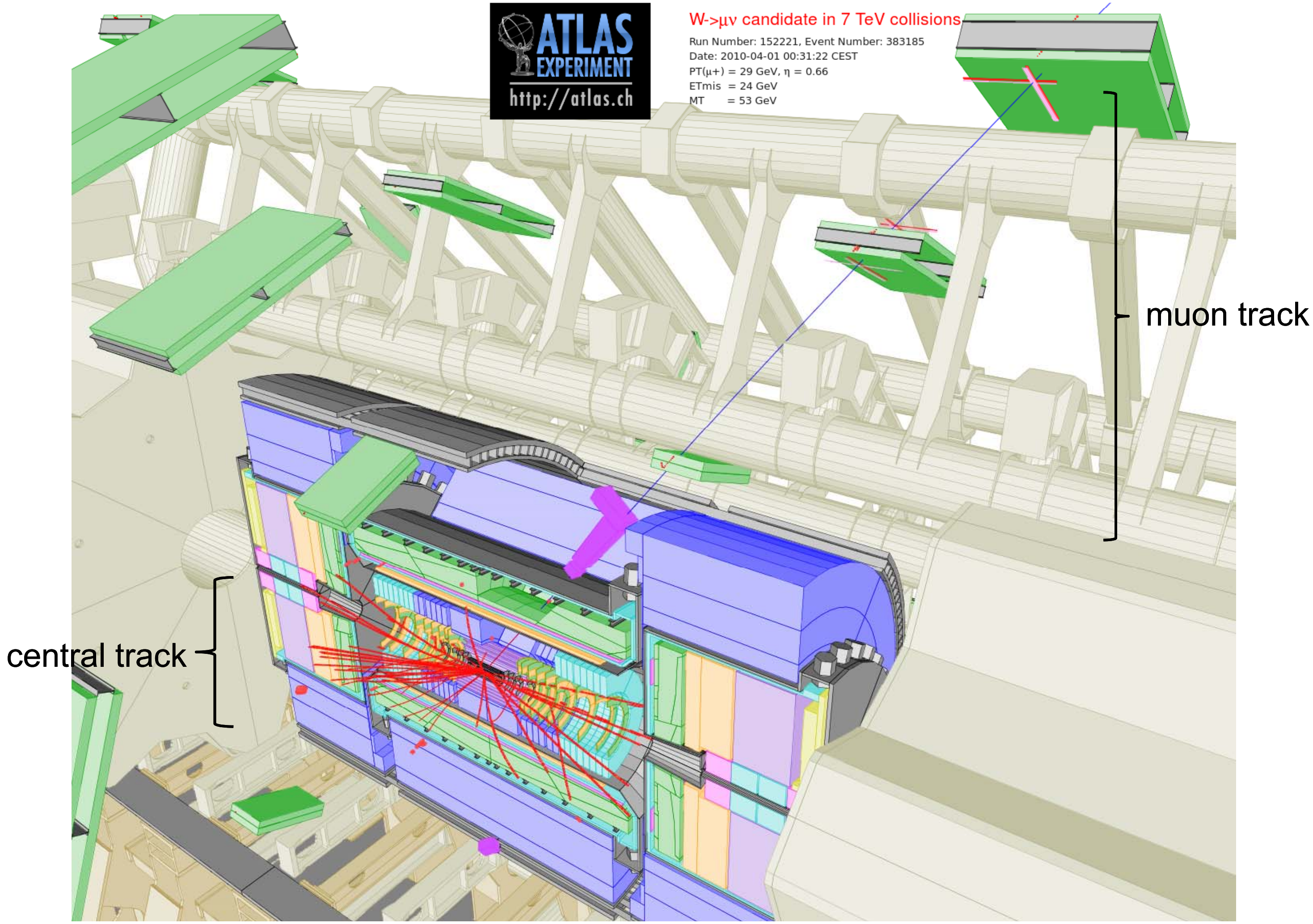


From a photon

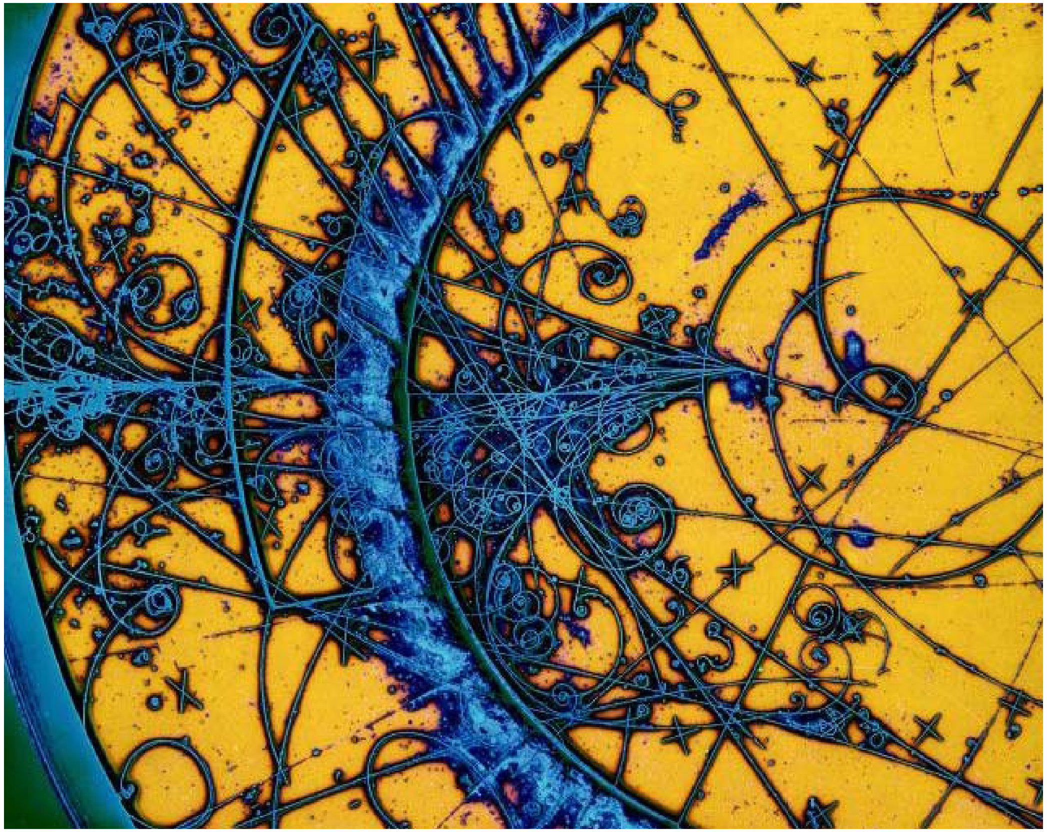


Why Tracking ?

We can create "global objects" associating hits and trajectories from different subsystems



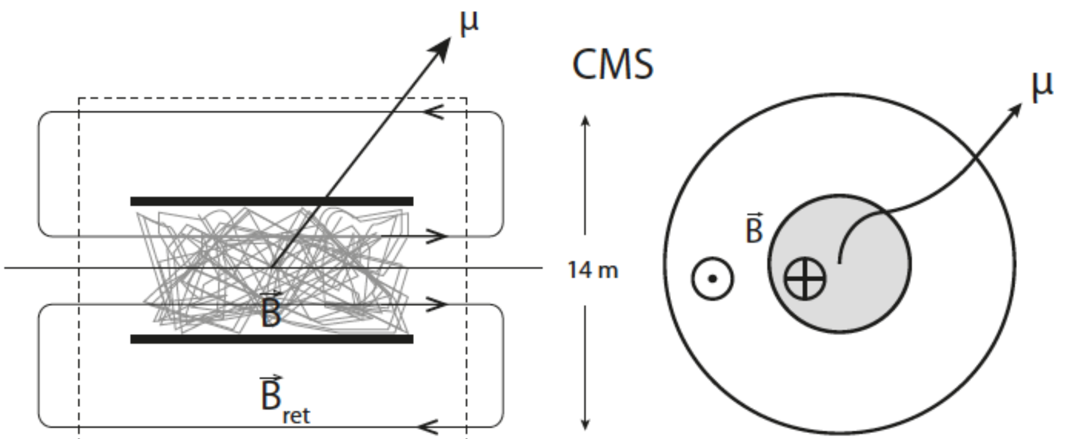
The Basic Ingredients



- A detector with high spatial resolution to measure the trajectory.
- A magnetic field to curve the trajectory and determine the momentum and charge
- A algorithm to “reconstruct” the trajectory from the hits in the detector
- ...and a good understanding of the interactions of our particle with matter

The choice of the magnet system…

Names CMS (Compact Muon System), ATLAS (A Toroidal LHC Aparatus) have the muon system behind

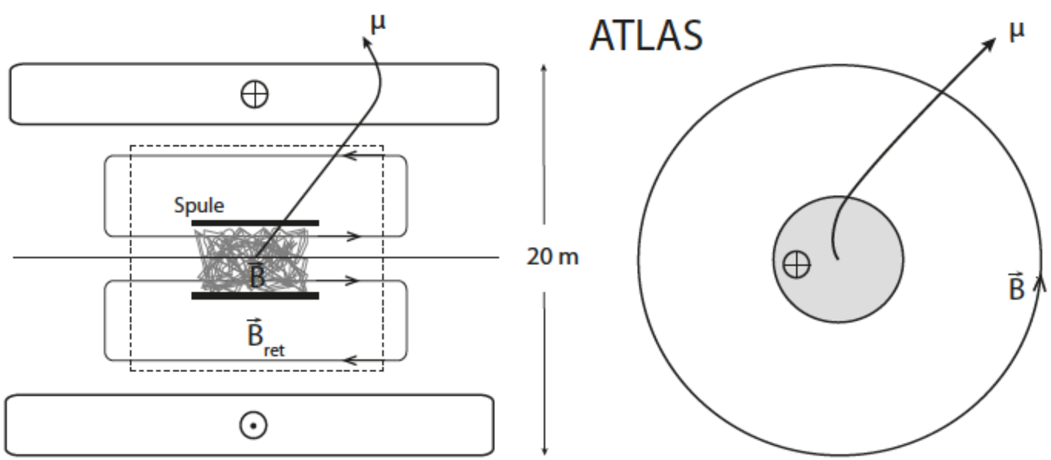


CMS

Momentum measured in tracker <u>and</u> B return flux

Solenoid with Fe flux return.

Property: μ tracks point back to vertex in R-Z plane



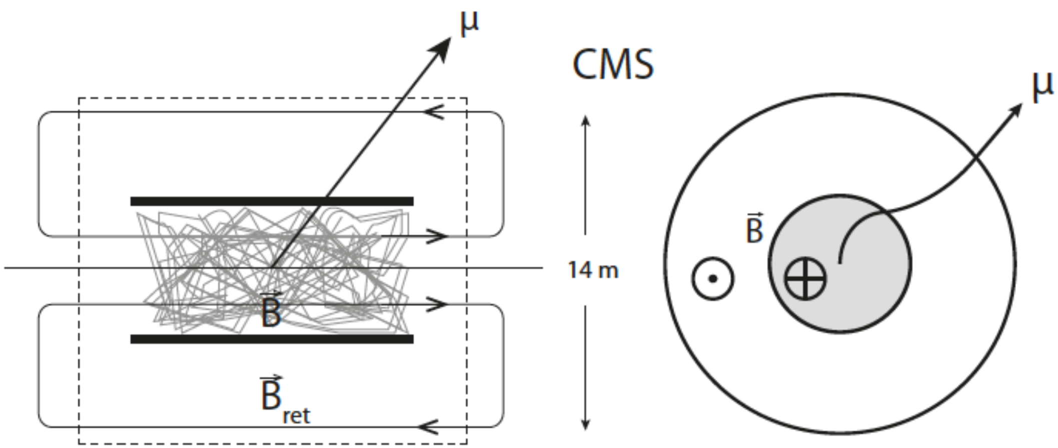
ATLAS

Standalone μ momentum measurement. Safe for high multiplicities.

Air-core toroid.

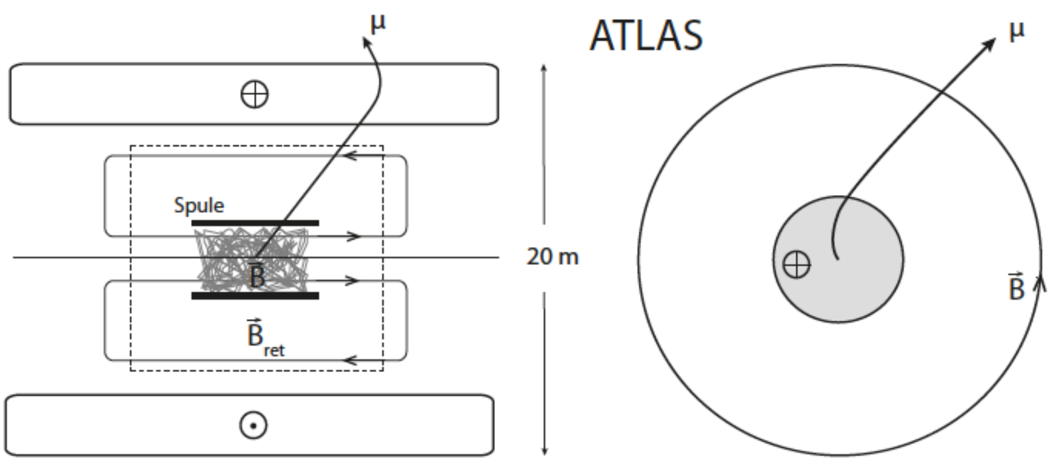
Property: σ_p constant in η

The reason behind the choice



CMS
Large (4T) field with very short (Fe) X_o

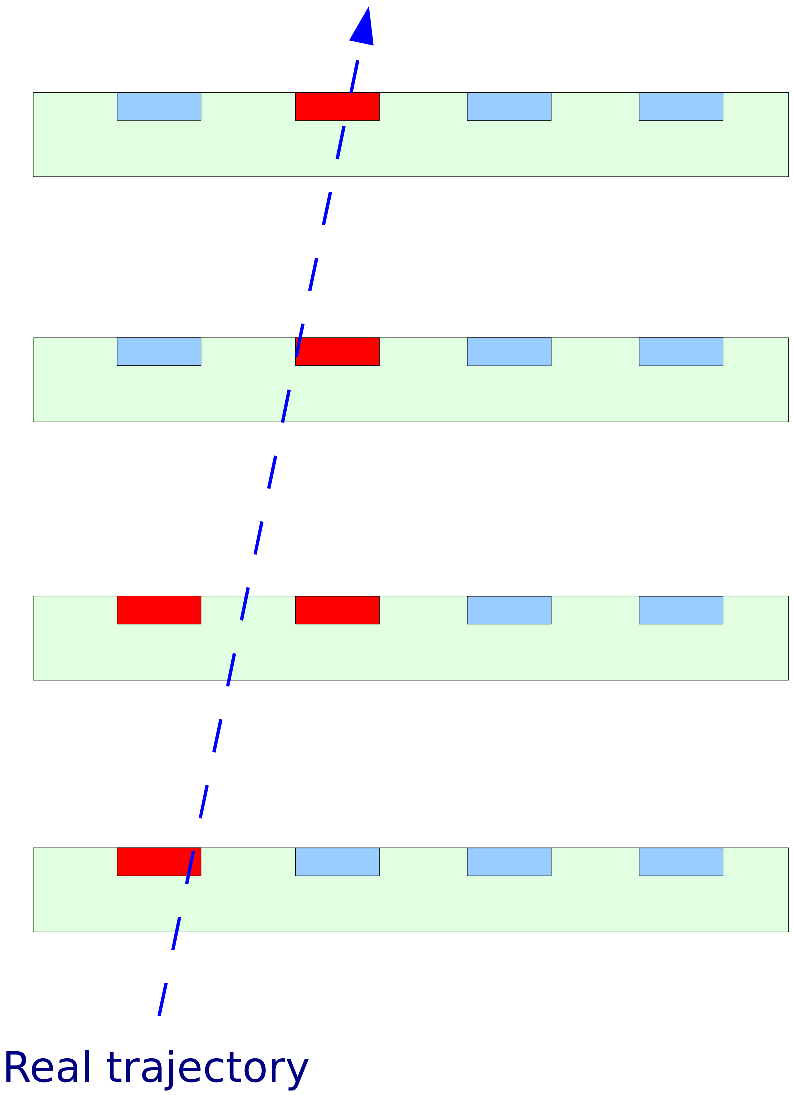
$$\frac{\delta p}{p}[ms] \sim \frac{\sigma_X}{B\sqrt{X_o \times L}}$$



ATLAS
Small (0.5T) toroidal field with very large (air) X_o

Signal "cooking"

- From raw data (hits) to tracks
  - The detector intrinsic resolution comes here.
- Need to distinguish genuine signals from noise
- Flag bad channels ("noisy")
  - Produce fake tracks
  - The set of bad channels might not be static
  - Operation conditions may change the set…
- Dead channels:
  - Inefficiency
  - Tracking resolution might be affected



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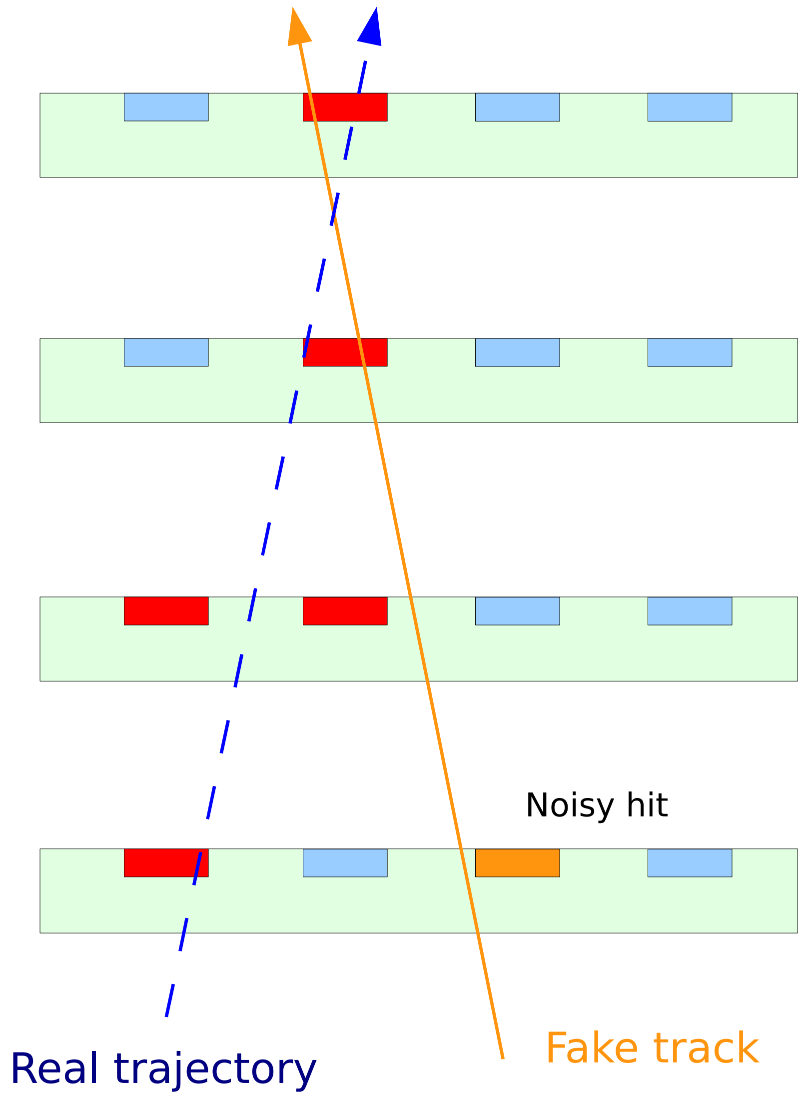

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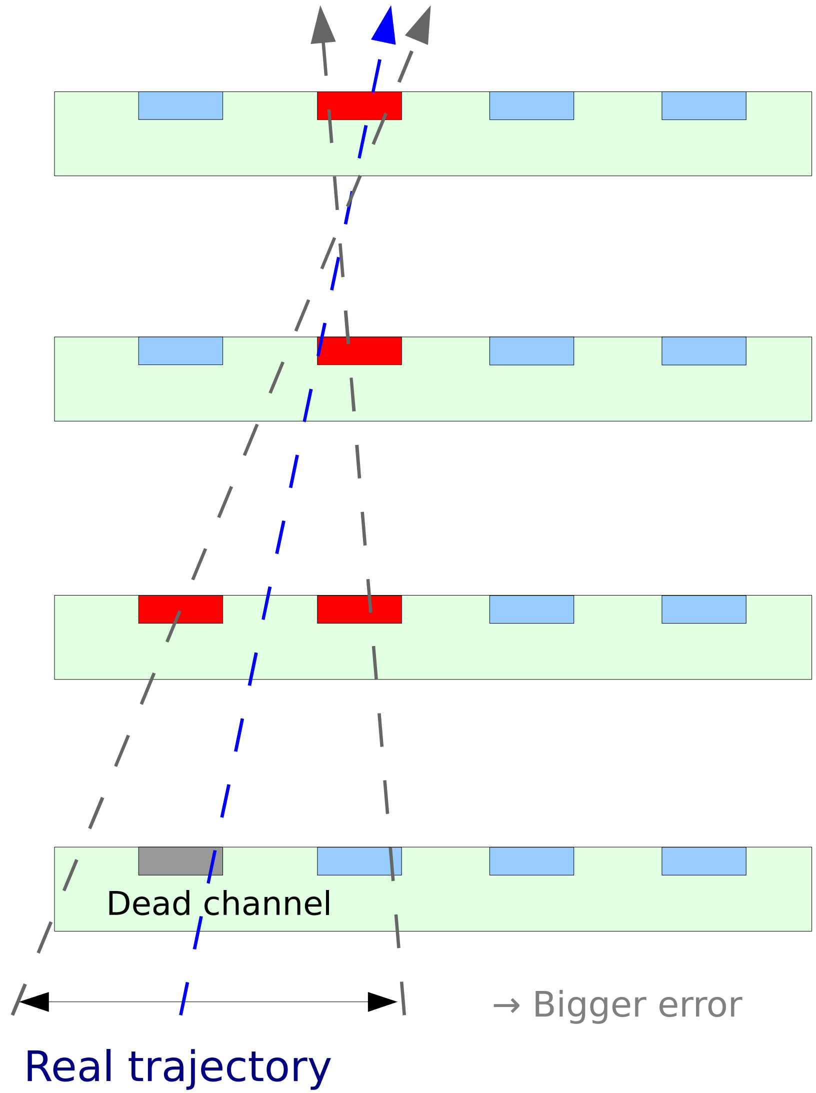
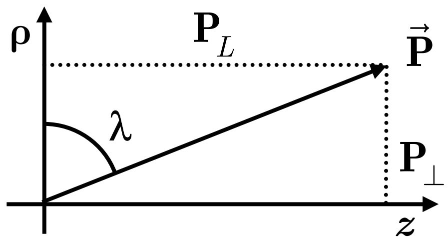


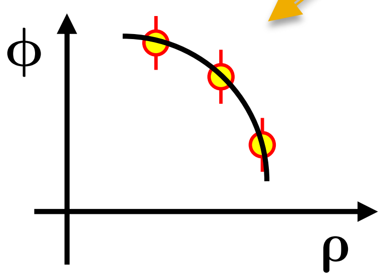
Momentum Measurement: solenoid

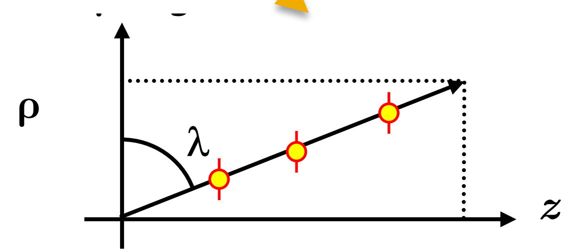
The Trajectory is an helix

The momentum of the particle is projected along 2 directions



We measure P_T in the ϕ-ρ plane





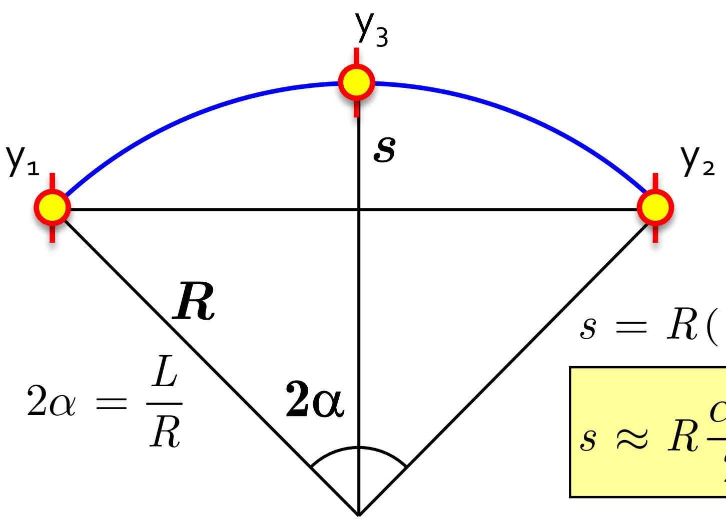
We measure dip angle λ in the ρ-z plane

$P_T = P \cos\lambda = 0.3\ B\ R$

The rule of the game: measure R with highest accuracy
What we really measure is the sagitta.

Momentum measurement: sagitta

$P_T = 0.3\,B\,R \rightarrow \frac{\delta p}{p} = \frac{\delta R}{R}$



$$2\alpha = \frac{L}{R}$$

$$s = R(1 - \cos\alpha)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

3 point measurement: y_1, y_2 an y_3
With a single hit resolution of δy
The track has a length L

$$s = y_3 - \frac{y_1 + y_2}{2} \rightarrow \delta s = \sqrt{\frac{3}{2}}\delta y \sim \delta y$$

$$\delta s = \frac{L^2}{8R}\frac{\delta R}{R} = \frac{L^2}{8R}\frac{\delta p}{p} \sim \delta y$$

$$\frac{\delta p}{p} = \frac{8p}{0.3BL^2}\delta y$$

- The relative error of the momentum
  - Degrades linearly with δy and p_T
  - Improves linearly with B
  - Improves quadratically with L
  - Improves as $\sqrt{N}$ with N the number of measurements (Gluckstern formula)
- A good momentum resolution calls for a **long track**.

$\frac{\delta p}{p^2}$ Is a good measure of a tracker performance

The price of High Accuracy

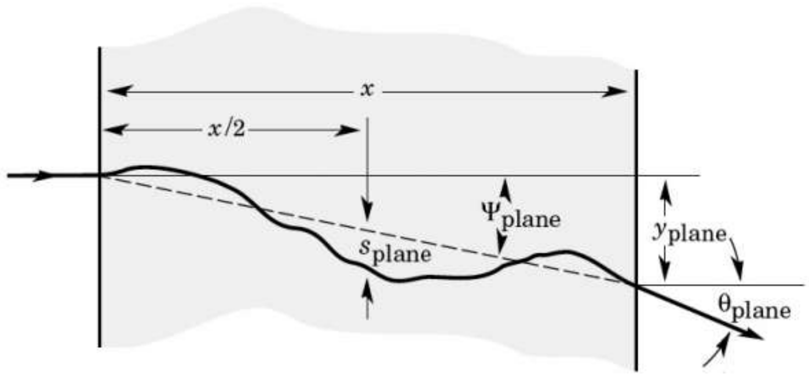
Multiple Coulomb Scattering

We already know this guy…

Introduces random angular errors and…

Adds an additional error to the momentum

$$\left.\frac{\sigma(p_T)}{p_T}\right|_{MS} = \frac{28\ \mathrm{MeV}}{0.3\ B\ L}\sqrt{\frac{x}{X_0}}\frac{p_T}{\beta\ c\ p}$$

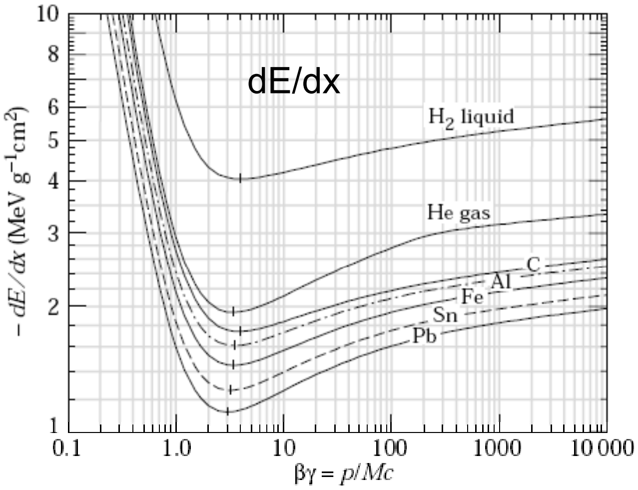


Ionization Energy Loss

Curvature decreases with path length.

Fluctuations in energy loss can be large if there is a lot of material/

$$\left.\frac{\sigma(p_T)}{p_T}\right|_{E_{loss}} \sim \frac{1}{p}\frac{x}{X_0}$$



Both effects decrease with p_T.

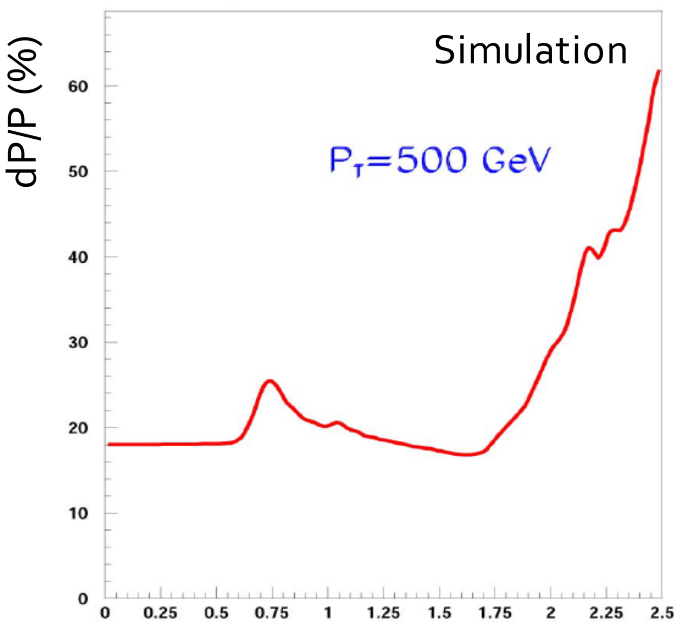
Momentum resolution: ATLAS

We can estimate what the performance would be for ATLAS.

Assume high momenta (no MS)
L ~ 75cm, B = 2 T, δy ~20 μm

$$\frac{\delta p}{p^2} = \frac{8}{0.3BL^2}\delta y \sim 4\times10^{-4}$$

At 500 GeV, dp/P ~ 20 %

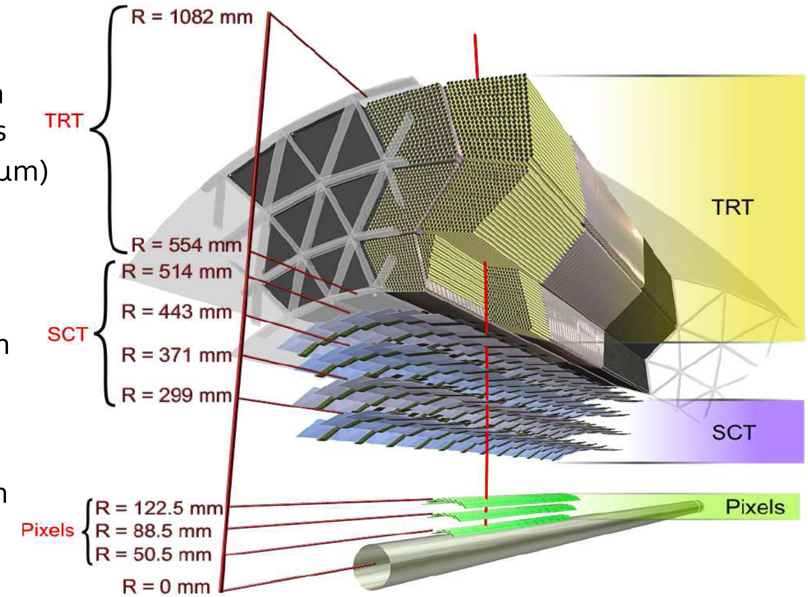


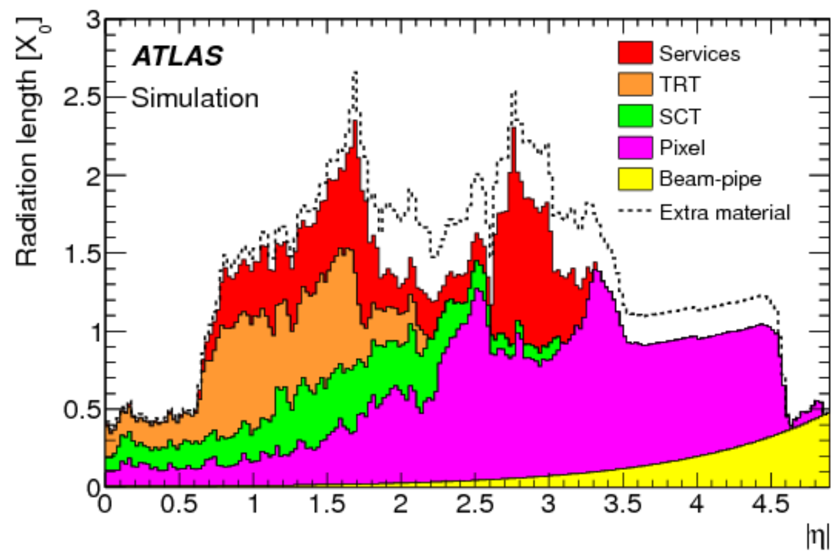
Why is it not constant ?

σ = 28µm (36 layers with 170 µm)

σ = 16 µm

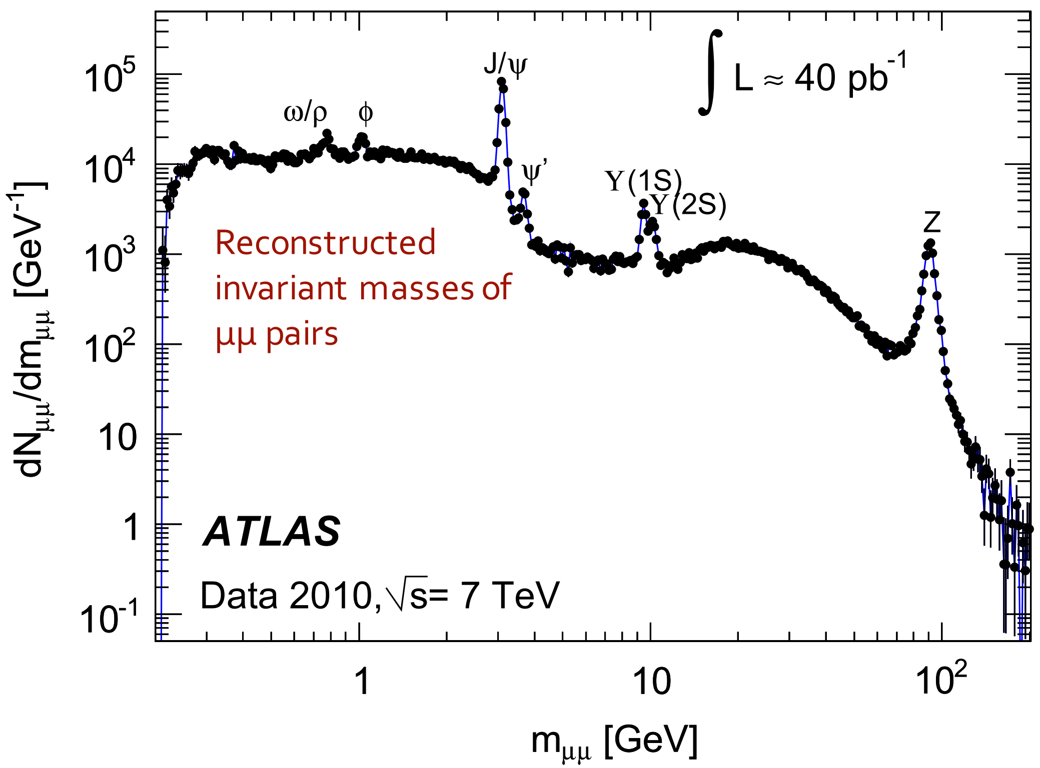
σ = 12 µm





That's not all, folks !!

- There are many things which are not covered here and are worth mentioning
  - Pattern recognition
  - Track fitting
  - Alignment ...
- They make possible that a detector as large and complex as ATLAS (or CMS) turn out to be so accurate...



Wraping up

- HEP data does not grow in trees. It does not come in cans or paper boxes neither…
  - I hope I it is clear that the road from collision to *digested* data for analysis is tortuous, yet rewarding…
- Up to here a bit biased towards tracking.
- Very important missing ingredients: calorimeters.. Do not be impatient…
  - Next session deals with them and their integration in the whole system: particle flow
- Finally, a thorough analysis of an existing detector: ATLAS