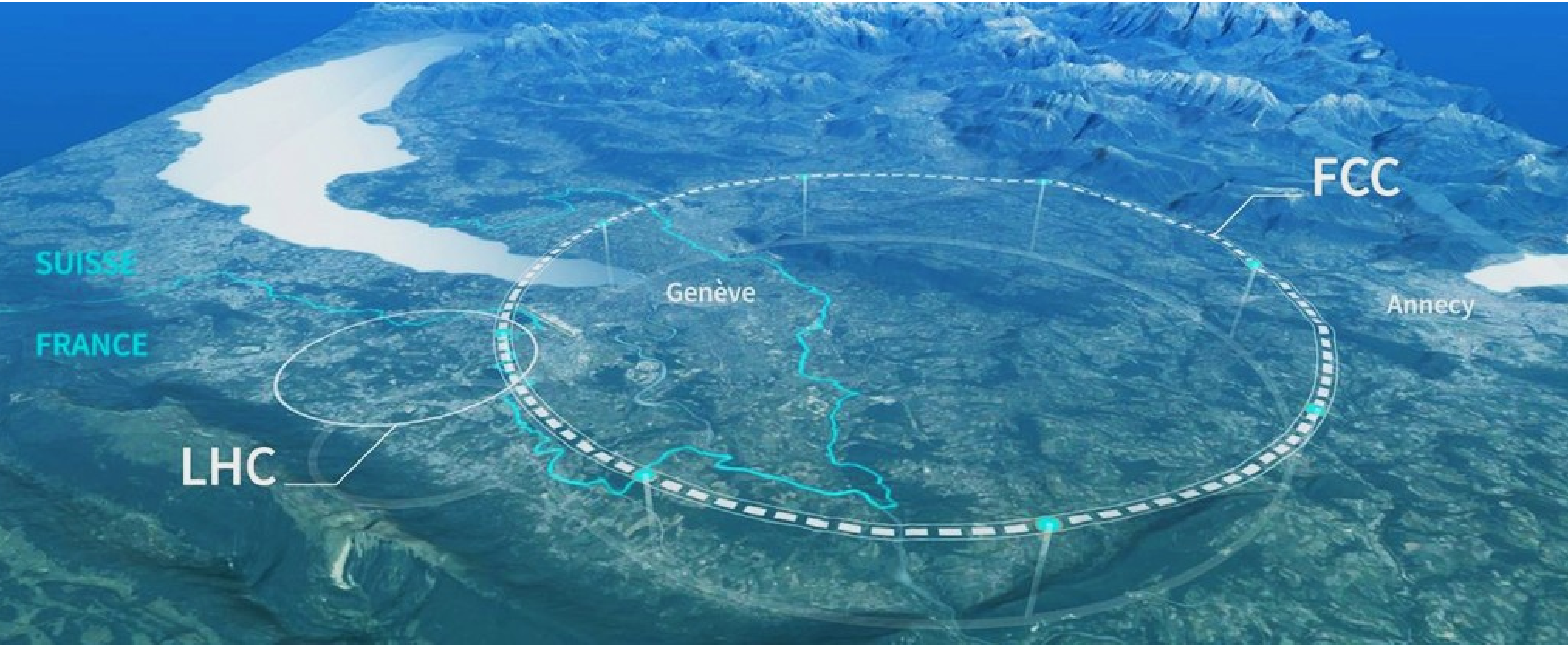
8.FCC - January Research Projects on
the Future Circular Collider (FCC-ee)

Particle Detectors
[January 13, 2025]



Lecture Outline

Particle Detectors Overview

- Introduction and a bit of history
- General organization of detectors
- Particle interactions with matter
- Tracking
- Calorimetry
- Modern integrated detectors
- Conclusions

Motherhood and Apple Pie

The ultimate goal of particle detectors is to determine the particles creation/decay point, its momentum and its type (mass).

Detecting particles always implies to interact with them. Its path is thus always affected by observation. If it's perfect it ain't real.

Particle detectors always rely on electromagnetic interaction (photons or charged particles).

Definitions and Units

Energy of a particle: $E^2 = p^2c^2 + m^2c^4$

- energy, E, measured in eV (= $1.6 \cdot 10^{-19}$ J)
- momentum, p, measured in eV/c
- mass, m, measured in eV/c^2
- $m_{\text{bee}} = 1$ g $= 5.8 \cdot 10^{32}$ eV/c^2

- $v_{\text{bee}} = 1$ m/s $\rightarrow E_{\text{bee}} = 10^{-3}$ J $= 6.25 \cdot 10^{15}$ eV
- $E_{\text{p,LHC}} = 14 \cdot 10^{12}$ eV, but all protons $10^{14} \rightarrow 10^{8}$ J

m = 100 T
v = 120 km/h

From special relativity

$$\frac{v}{c} = \beta \quad (0 \le \beta < 1) \quad \text{and} \quad \gamma = 1/\sqrt{1-\beta^2} \quad (1 \le \gamma < \text{inf})$$

Definitions and Units

Cross Section, σ

- cross section or differential cross section expresses probability of a process to occur
- two colliding bunches: N_1/t collides with N_2/t
- rate is $$R_{\text{int}} \propto \frac{N_1 N_2}{At} = \sigma L$$

cross section is an area
1 barn = 10^{-24} cm^2

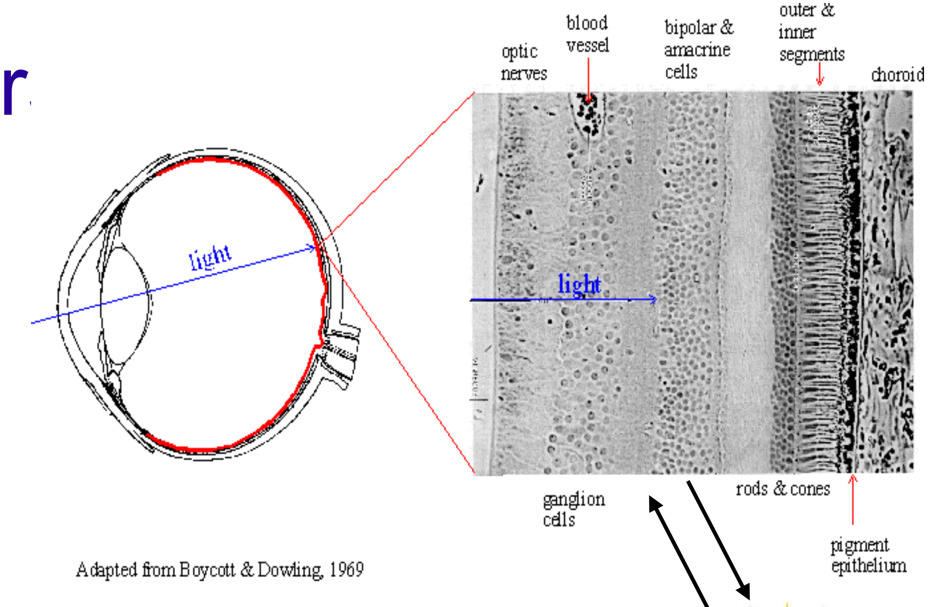
luminosity [cm^{-2} s^{-1}]

- Differential cross section: $$\frac{d\sigma}{d\Omega}$$
- fraction of cross section scattered in dΩ angular area

Natural Particle Detectors

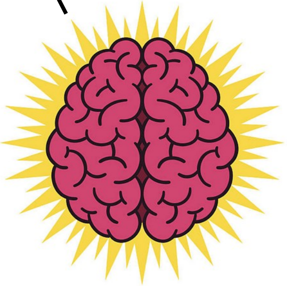
Very common particle detector

the eye



Adapted from Boycott & Dowling, 1969

Retina as seen



Properties of 'eye' detector

- highly sensitive to photons
- decent spatial resolution
- excellent dynamic range 1-10^{14}
- automatic threshold adaptation
- energy discrimination, though limited range: wavelength
- modest speed: data taking at 10 Hz, inc. processing
- excellent data processing connection (at times)

Extending the Eye

Photographic paper as detector

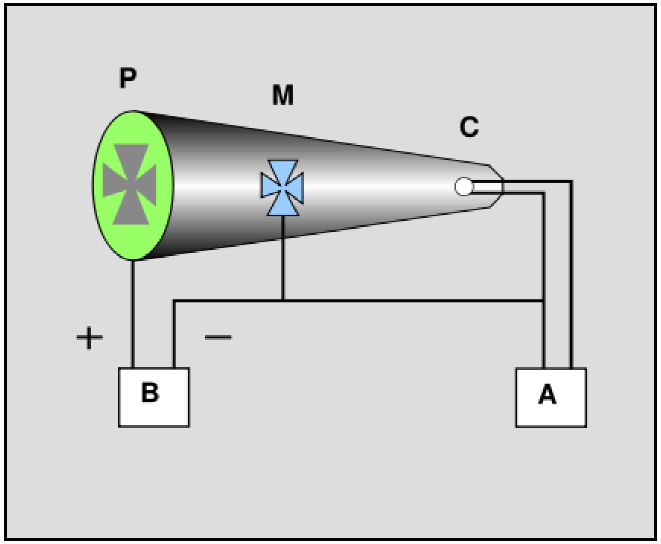
- 1895 W.C. Röntgen (first Nobel prize in physics)
- detection of photons (x-rays) invisible to the eye
- Silver bromide or chlorides (emulsion)
- AgBr + energy → silver (black)

Properties of 'paper' detector

- very good spatial resolution
- good dynamic range
- no online recording
- no time resolution

The Cathode Ray

1897 J.J.Thomson discovers the electron



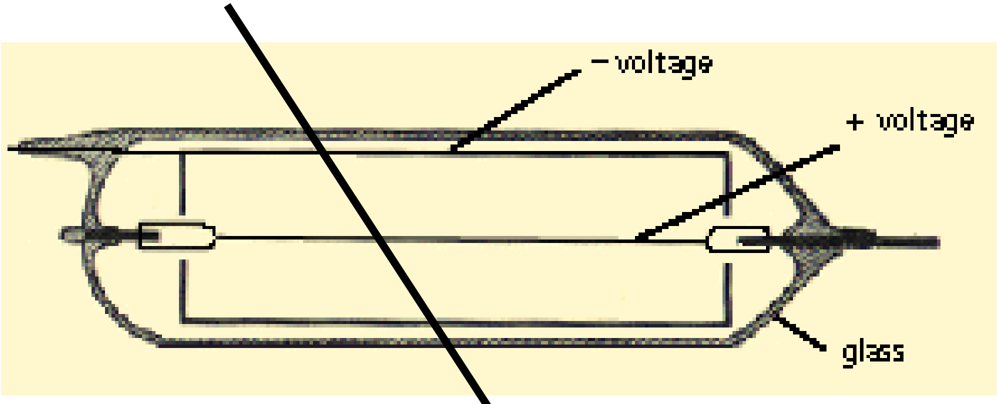
From his publication:

*"Cathod Rays": Philosophical Magazine, **44**, 293 (1897)*

… The rays from the cathode C pass through a slit in the anode A, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit in another earth-connected metal plug B, they travel between two parallel aluminum plates about 5 cm. long by 2 broad and at a distance of 1.5 cm. apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflection of this patch….

Scintillation of glass caused the visible light patch

The First Electrical Signal



The Geiger counter

- a gas volume
- anode and cathode
- passing charge particle ionizes the gas
- ionization drifts:
  - ion – cathode
  - electron – anode
- pulse can be used in various ways, for example as a 'click' on a little speaker

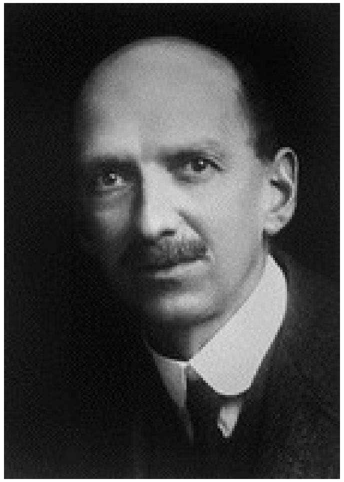
Improved version called Geiger-Müller

Hans Wilhelm Geiger (1928)

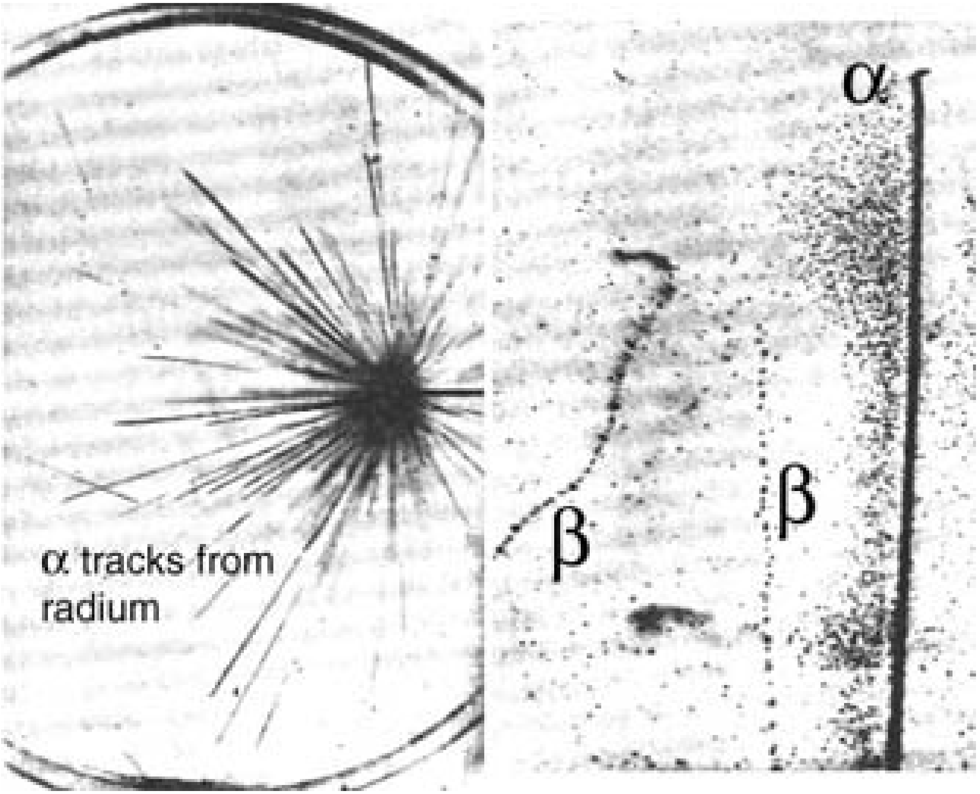
The First Tracking Detector

The Cloud Chamber

- an air volume saturated with water
- lower pressure to generate a super-saturated air volume
- charged particles cause
- condensation of vapor into
- small droplets
- droplets form along particle
- trajectory and are observed
- photographs allow longer
- inspections



Charles.T.R Wilson



Detectors and Particle Physics

Fruitful connection (experimenters/theorists)

- detectors allow one to detect particles
- experimenters study their behavior (informed by theory predictions)
- new particles are found by direct observation or by analyzing their decay products
- theorists predicts behavior of (new) particles
- experimentalists design the particle detectors to detect them and collect the data

Overview of Detectors

What do particle detectors measure?

- spacial locations
- momentum
- energy
- flight times

Modern detector types

- tracking (gas, solids)
- scintillation and light detectors
- calorimeters
- particle Id systems

Integral piece of detectors

- trigger systems
- data acquisition systems
- offline system

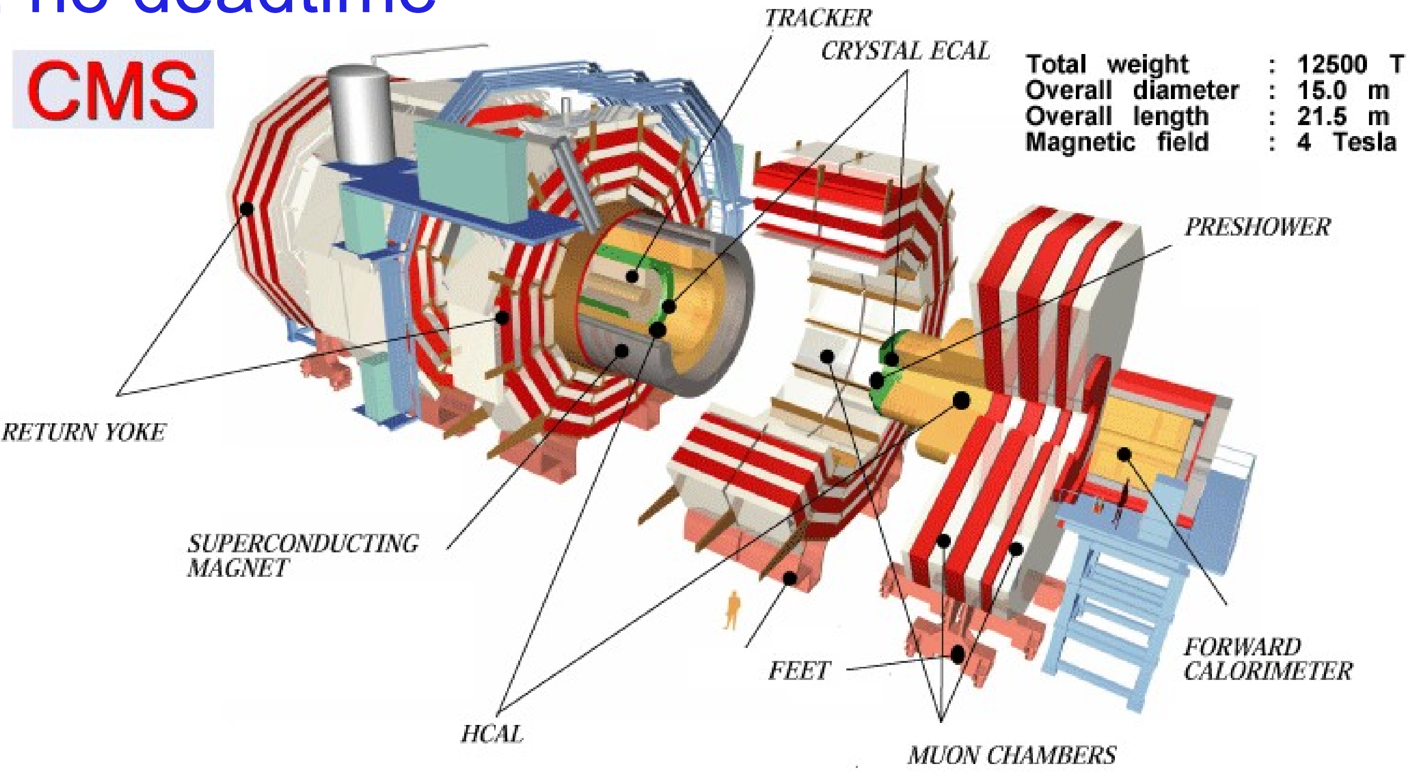
The Ideal Detector

Properties

- cover the full solid angle
- measurement of momentum and/or energy
- detect, track and identify all particles
- fast response, no deadtime

Limitations

- technology
- space
- budget



Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla

Following a Particle

Scattering with the nucleus, charge *Z* (Rutherford)

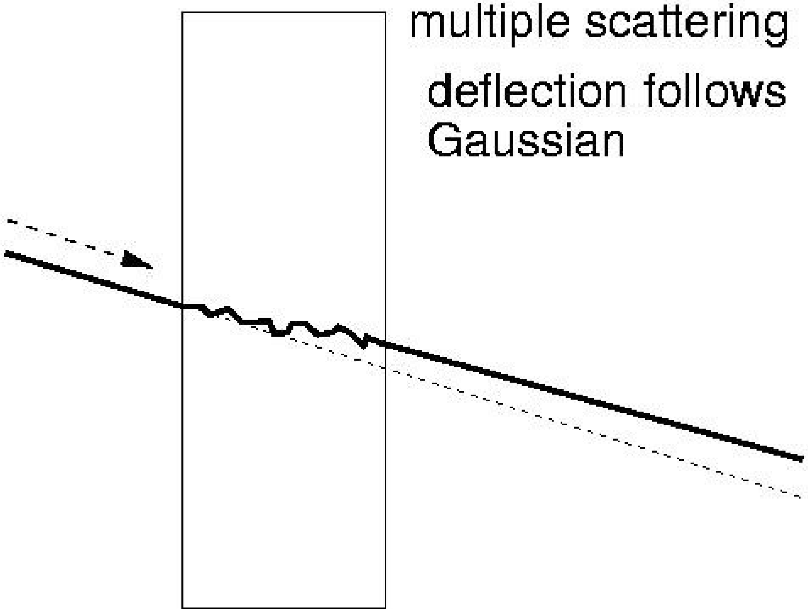
$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$

Particles do not scatter or very little

- if the material is thick they may scatter multiple times

Multiple scattering

- particle scatters multiple times
- the smaller the momentum the larger the effect
- Approximate by Gaussian around original direction



Following the Particle

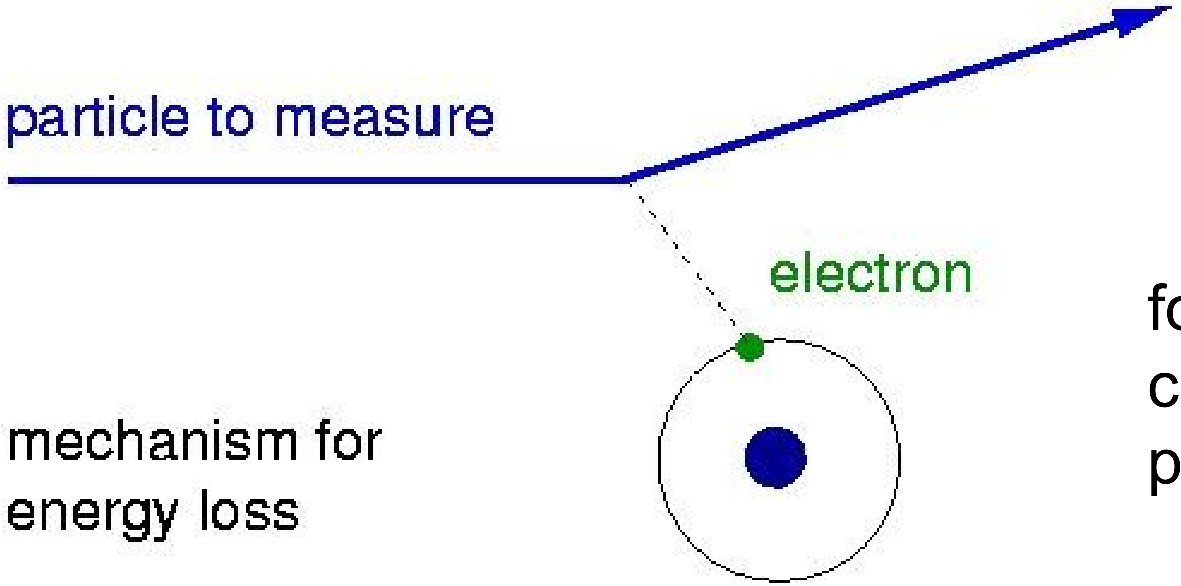
Energy loss in matter

- multiple scattering? no! collision elastic (heavy nucleus)
- scattering with electrons from the atoms
- energy loss per length *x*

$$\frac{dE}{dx} = -\int NE \frac{d\sigma}{dE} \hbar d\omega.$$

electron density

cross section per energy



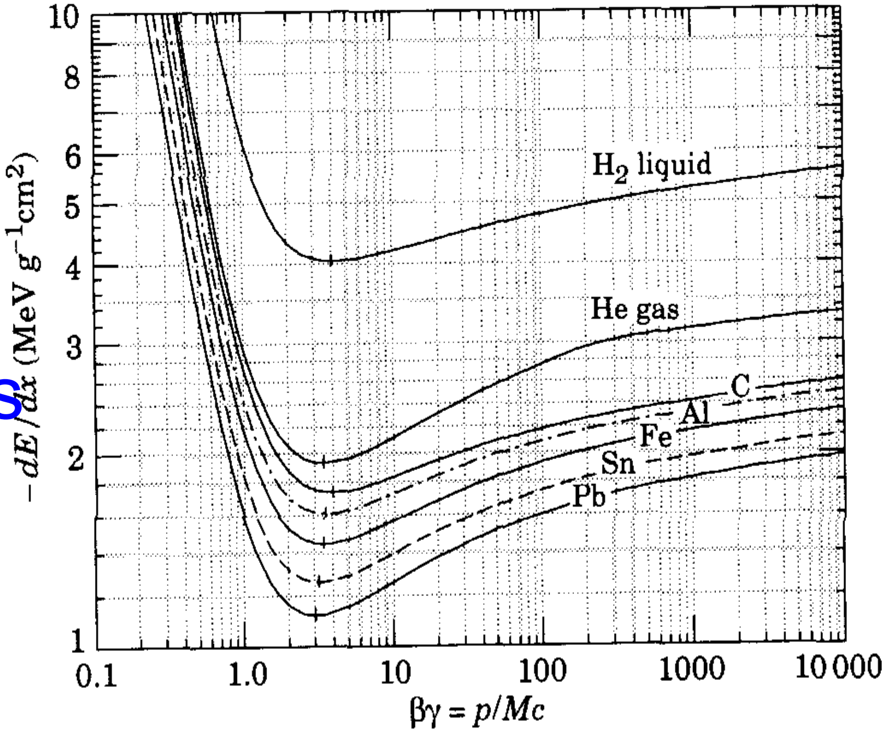
for large enough interaction causes ionization, sometimes photon exits medium (later)

Bethe-Bloch Formula

Average differential energy loss *dE/dx*

$$\frac{dE}{dx} = -4\pi N_A r_e^2 c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

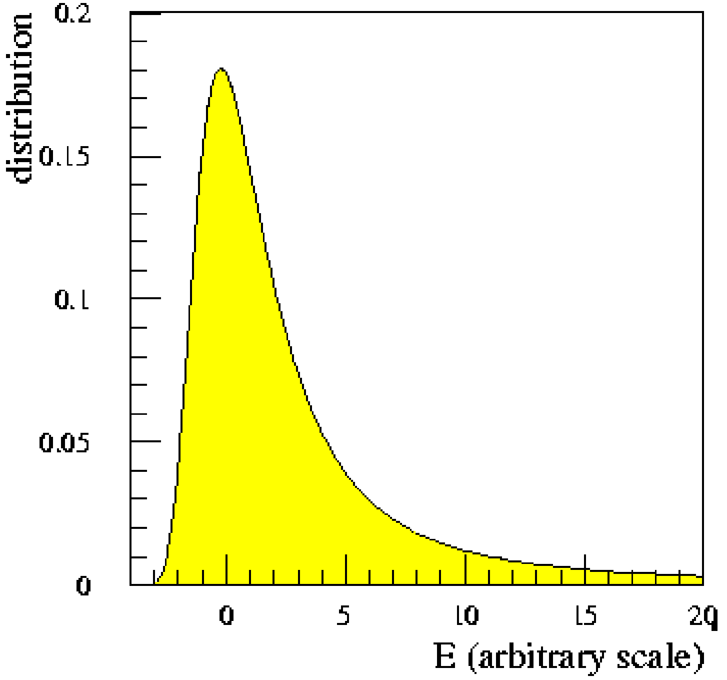
- in MeV/g/cm^2
- only valid for “heavy” particles ($m>m_\mu$)
- independent of *m*, only depends on β
- to first order proportional to *Z/A* (density of electrons)

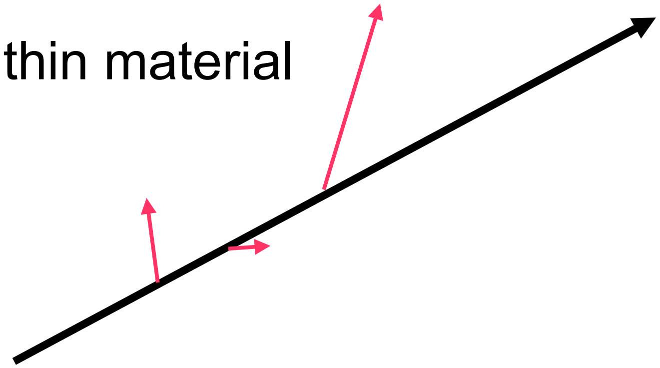


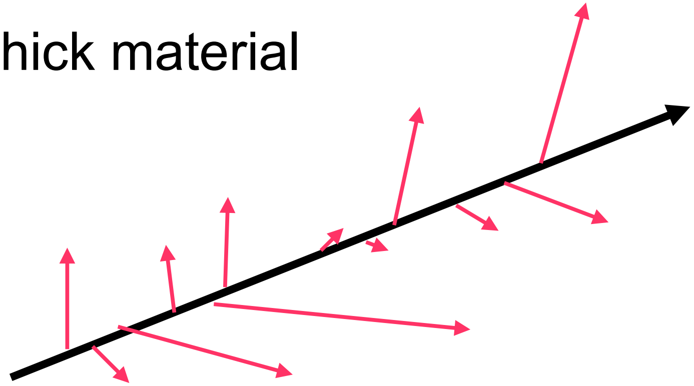
Practical Issues of Energy Loss

Energy loss is measured on finite path δx not dx

- thin material few discrete collisions
- causes large fluctuations and long tails
- for thick material many collisions and energy loss distribution looks more like a Gaussian



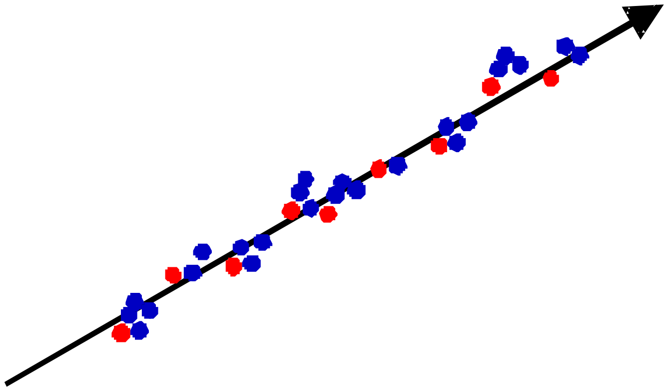

thin material

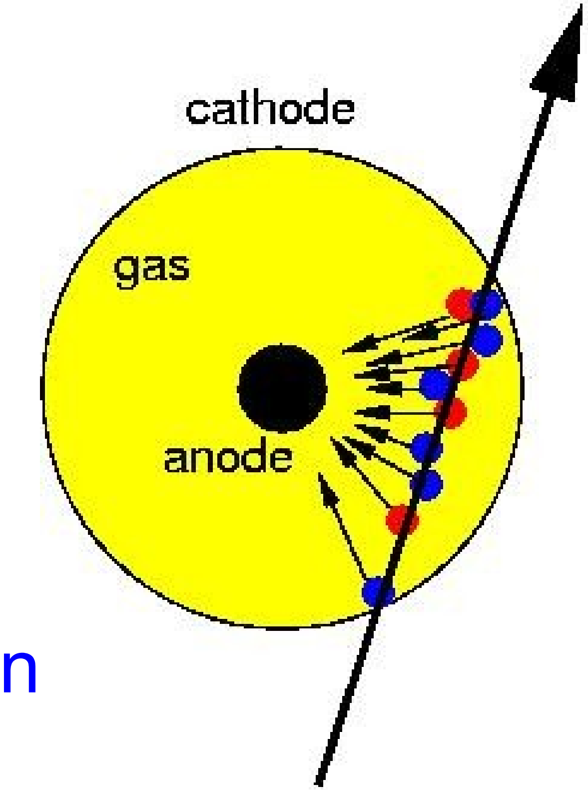

thick material

Tracking in Gas Detectors

Charged track ionizes the gas

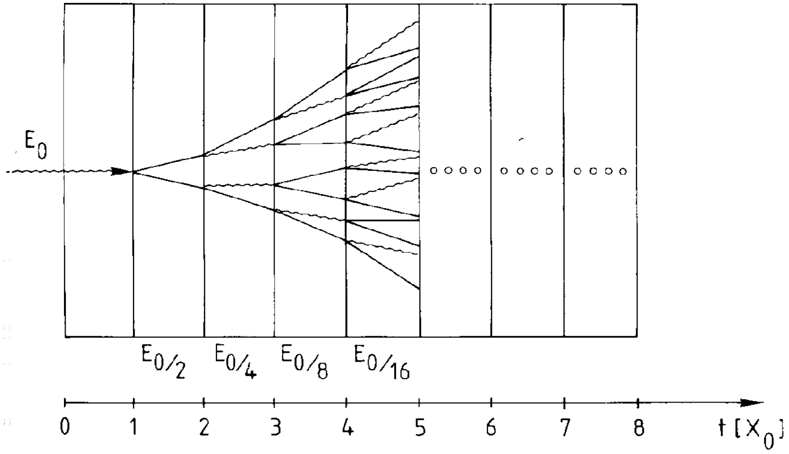
- 10-40 primary ion-electron pairs
- secondary ionization x 3 to 4
- → about 100 ion-electron pairs
- cannot be effectively detected
- amplifier noise about 1000 e^{-}
- number of ion-electron pairs has to be increased!
- velocity versus cathode increases
- electrons cause avalanche of ionization (exponential increase)





Calorimetry

General idea

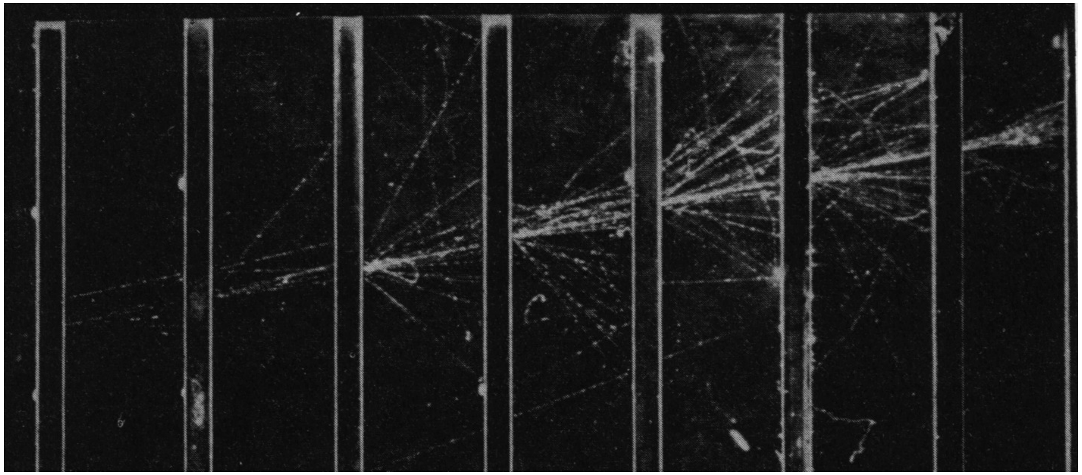


- measure energy by total absorption
- also measure location
- method is destructive: particle is stopped
- quantity of detector response proportional to energy
- calorimetry works for all particles: charged and neutral
- mechanism: particle is forced to shower by the calorimeter material
- .... but in the end it is again ionization and excitation of the shower products which deposits the energy
- we distinguish electromagnetic and hadronic showers

Calorimetry: Electromagnetic

Electromagnetic shower

- Bremsstrahlung
- pair production
- quite simple shower
- electrons/photons only interact electromagnetically

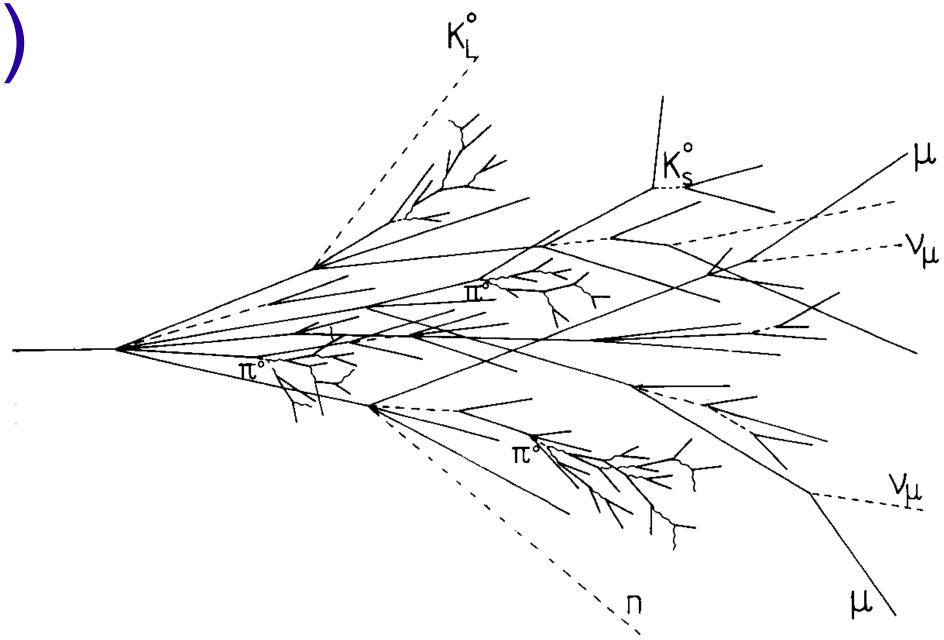


Cloud chamber with lead absorbers

Photons either pair produce electron-positron or excite the atom or do Compton scattering
Large charge atoms are best materials, but also organic material is used: radiation length

Calorimetry: Hadronic

Hadronic cascades (showers)



- different processes involved
- EM showers included
- plus hadronic showers
  - generating pions, kaons, protons
  - breaking up nuclei
  - also creating non detectable: neutrons, neutrinos, soft photons
  - energy sum more difficult
  - large fluctuation and limited energy resolution
- choose dense materials with large A: Uranium, Lead, ..
- nuclear interaction length determines depth of shower

Muon Detection

Muon is basically a track

- do standard tracking tricks

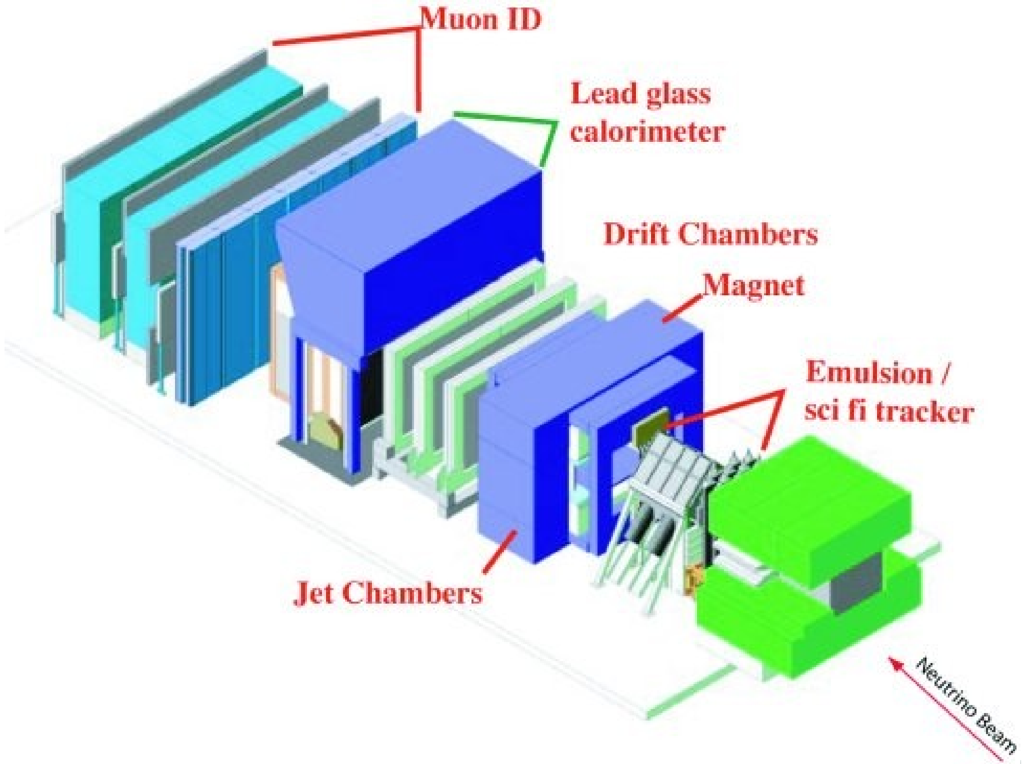
But muons are minimally ionizing

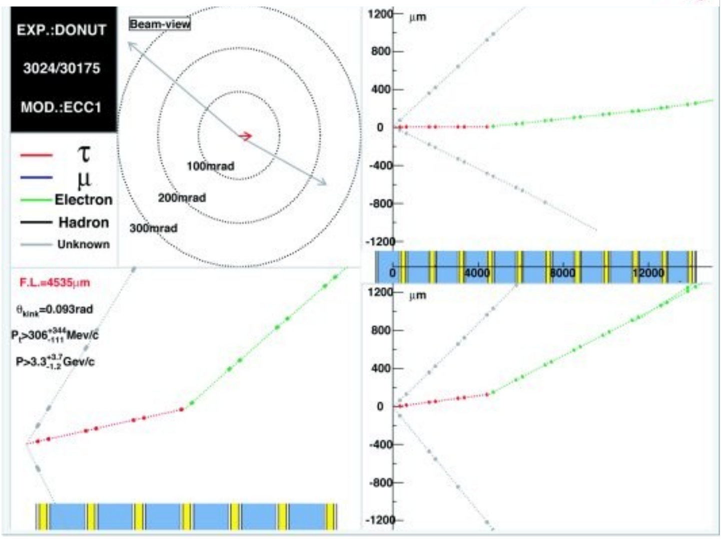
- penetrate through a lot of material
- it makes calorimetry with muons special
  - does not get stuck in the calorimeter (missing energy)
  - signature is recognizable and is used for selection of muons
- muons are really identified outside of the calorimeters they are the last remaining particles after calorimeter absorption (there are also neutrinos of course ...)
- typically at least 4 nuclear interaction length shield the muon detectors

Modern Photographic Emulsions

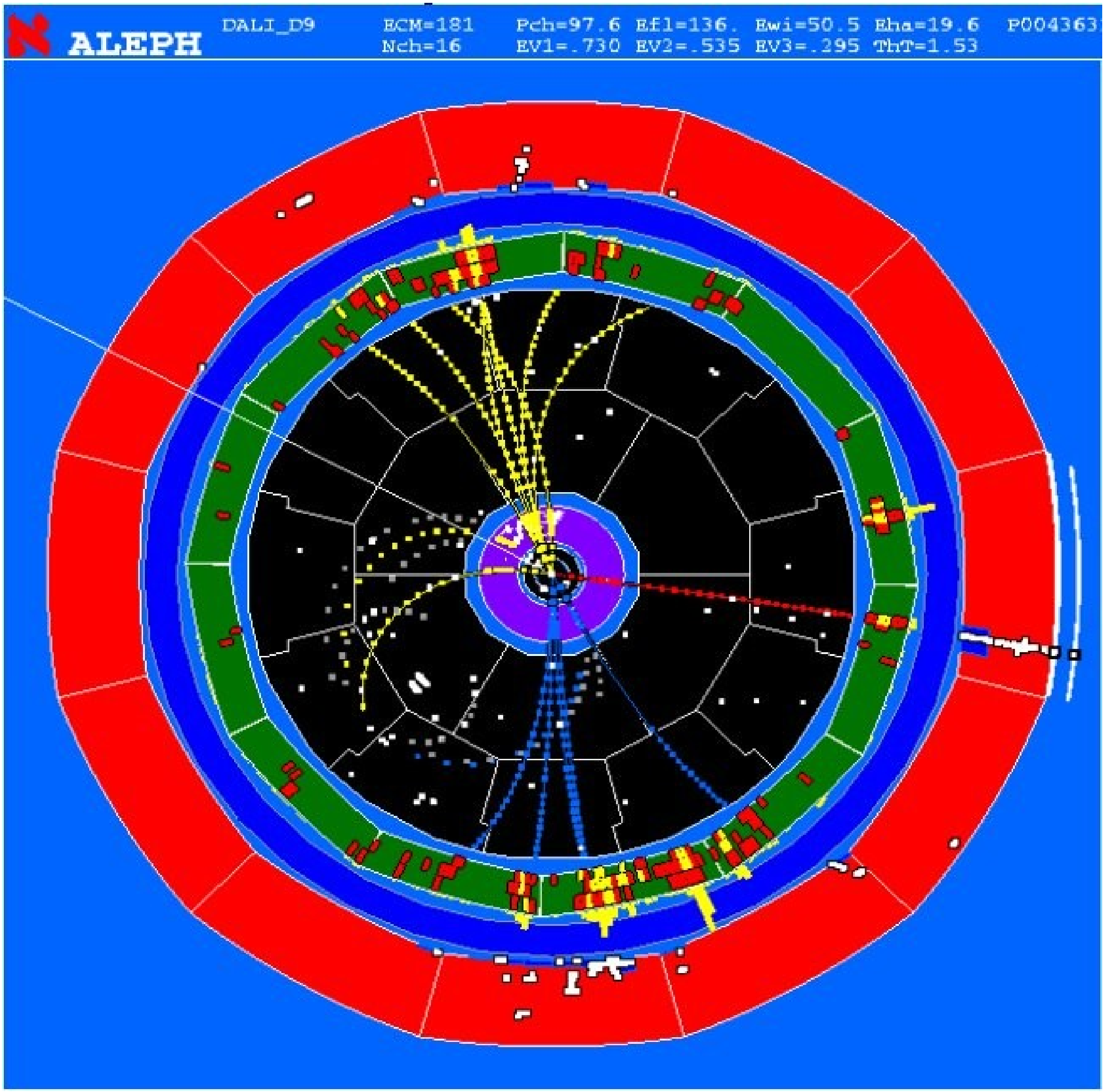
Emulsions

- cannot be readout electronically
- scan optically
- has been fully automated
- low rate experiments only
- provide very precise locations better than 1 µm
- example: discovery of the τ neutrino – DONUT
- CHORUS also used them



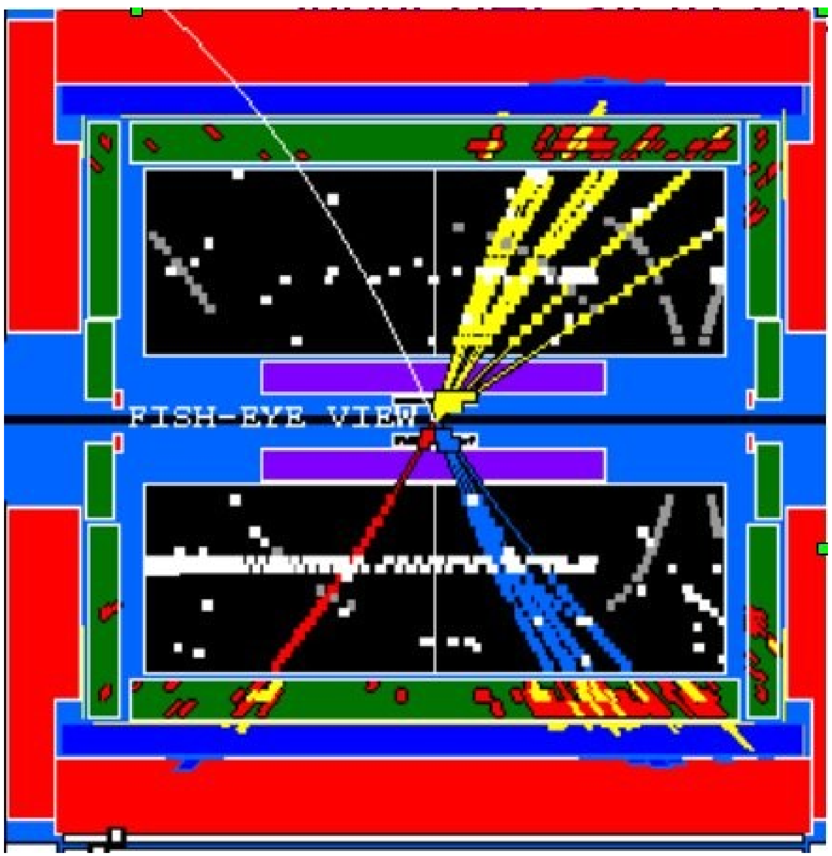


Examples of Modern Detectors



WW decay in Aleph

qq $\mu\nu_\mu$



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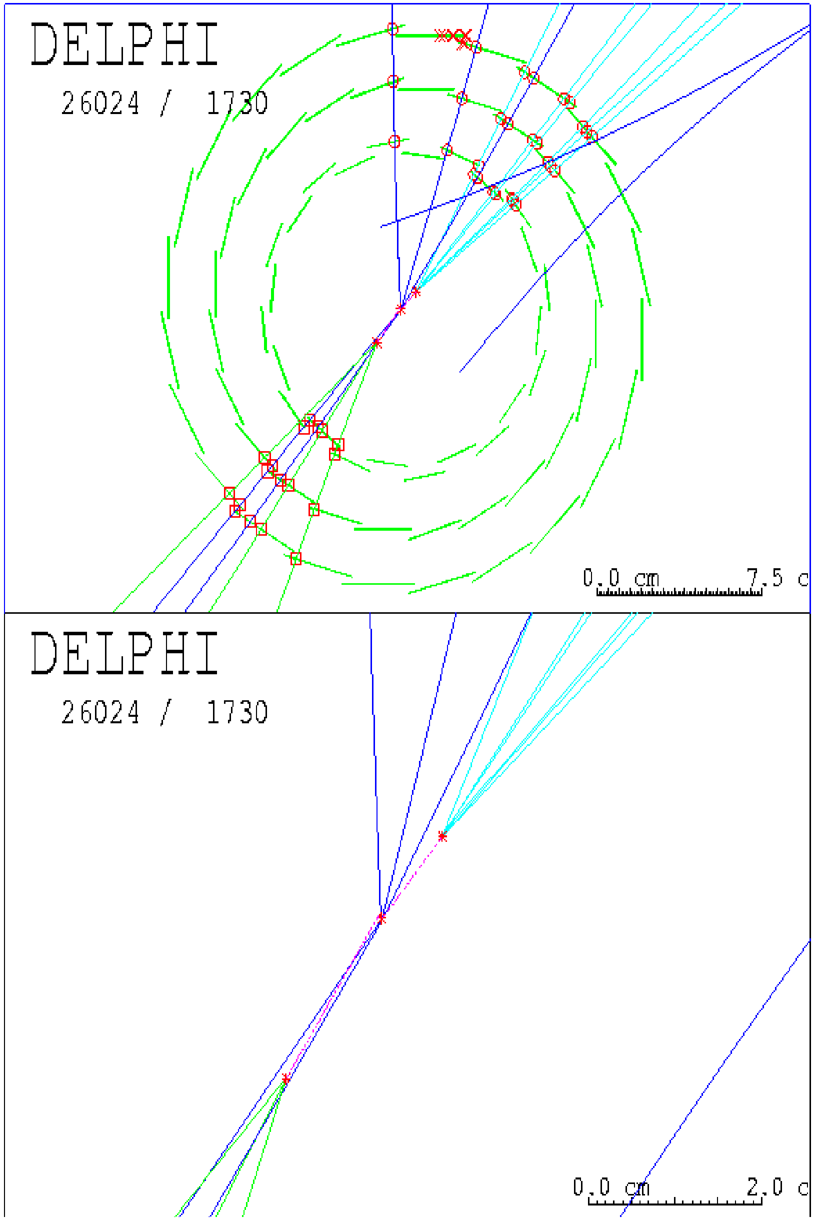

Delphi Detector

- *B* meson in micro vertex detector
- *B* flies for about 1 milimeter
- 3 layers
- waver structure visible
- resolution: 10s of μm

For the FCC-ee

- Planning to get to 3 μm
- More then 3 layers for sure

Conclusion

Particle detectors follow simple principles

- detectors interact with particles
- most interactions are electromagnetic
- imperfect by definition but have gotten pretty good
- crucial to figure out what detector type goes where

Four main ideas

- track charged particles and then stop them
- stop neutral particles
- find the muons which are left
- Measure what is missing from energy conservation