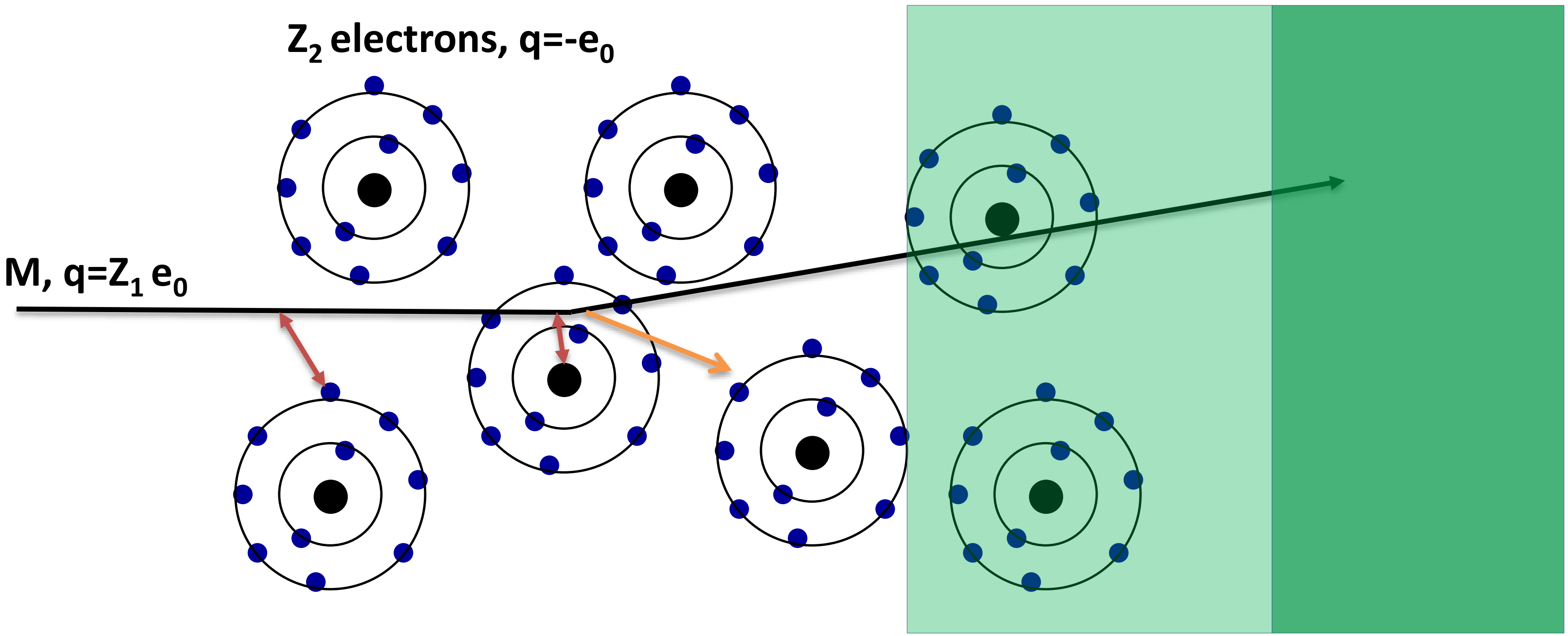
Детектори

Electromagnetic Interaction of Particles with Matter



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are <u>excited</u> or <u>ionized.</u>

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as <u>Cherenkov Radiation</u>. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

Bethe - Bloch formula

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Electron Spin

$$\delta(\beta\gamma) = \ln h\omega_p/I + \ln\beta\gamma - \frac{1}{2}$$

Density effect. Medium is polarized

Which reduces the log. rise.

Bethe Bloch Formula

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2 \,\frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

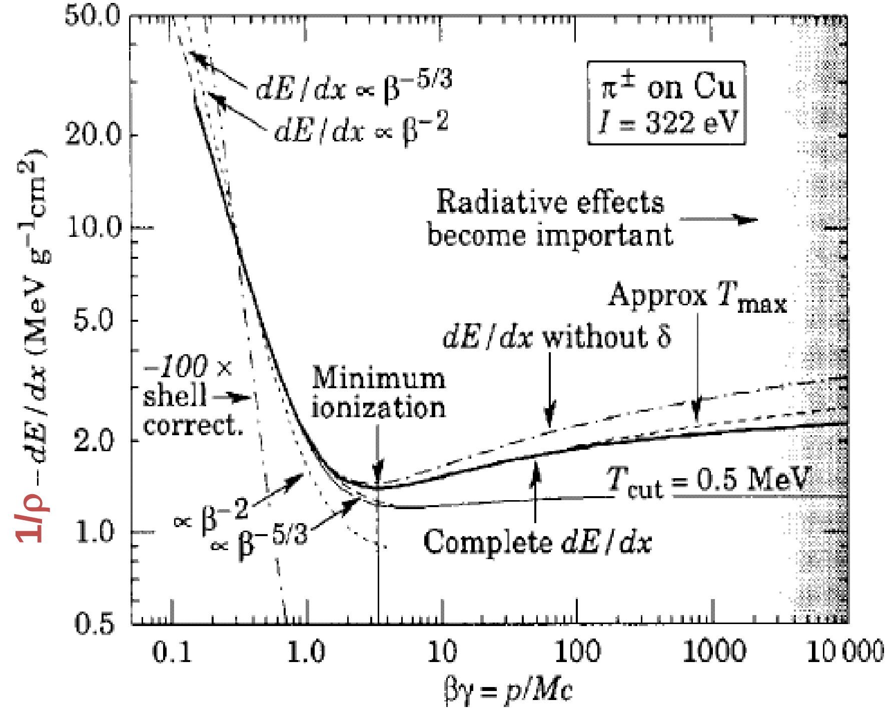
$Z>1$, $I \approx 16 Z^{0.9}$ eV

For Large $\beta\gamma$ the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss → density effect

At large Energy Transfers (delta electrons) the liberated electrons can leave the material.

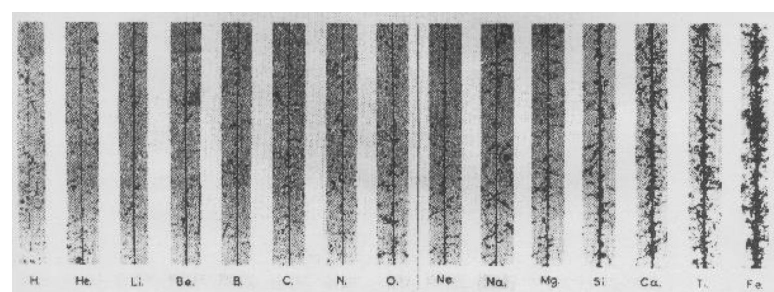
In reality, E_{max} must be replaced by E_{cut} and the energy loss reaches a plateau (Fermi plateau).

Characteristics of the energy loss as a function of the particle velocity ($\beta\gamma$)



The specific Energy Loss $1/\rho\ dE/dx$

- first decreases as $1/\beta^2$
- increases with $\ln\gamma$ for β =1
- is ≈ independent of M ($M \gg m_e$)
- is proportional to Z_1^2 of the incoming particle.
- is ≈ independent of the material (Z/A ≈ const)
- shows a plateau at large $\beta\gamma$ (>>100)
- $dE/dx \approx$ (1-2) ρ [g/cm³] MeV/cm



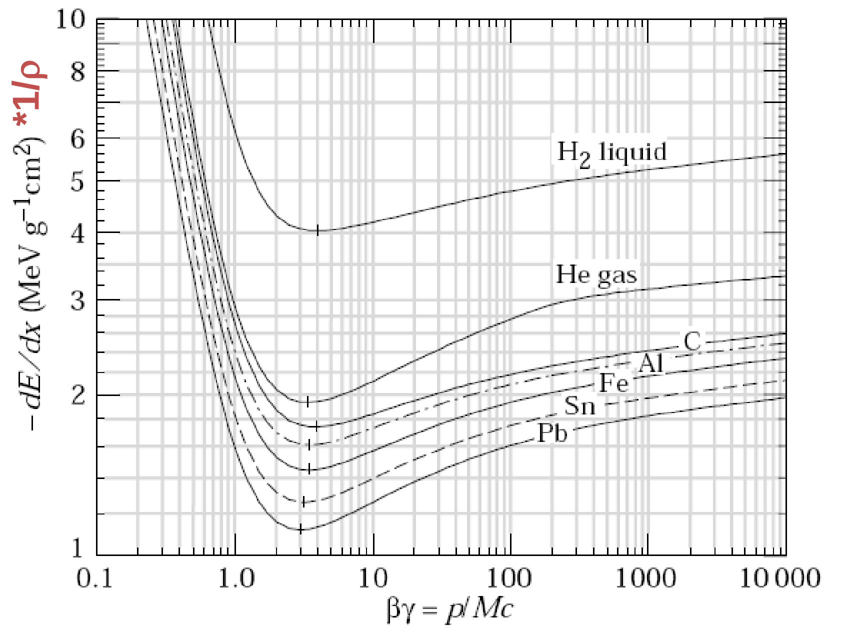
Bethe Bloch Formula

Bethe Bloch Formula, a few Numbers:

For Z ≈ 0.5 A
1/ρ dE/dx ≈ 1.4 MeV cm ^{2}/g for ßγ ≈ 3

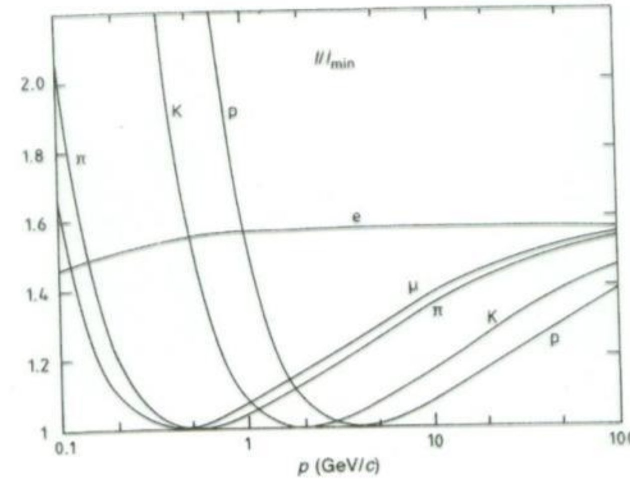
Example :
Iron: Thickness = 100 cm; ρ = 7.87 g/cm^3
dE ≈ 1.4 * 100* 7.87 = 1102 MeV

→ A 1 GeV muon can traverse 1m of Iron



This number must be multiplied with ρ [g/cm^3] of the Material → dE/dx [MeV/cm]

Energy Loss as a Function of the Momentum

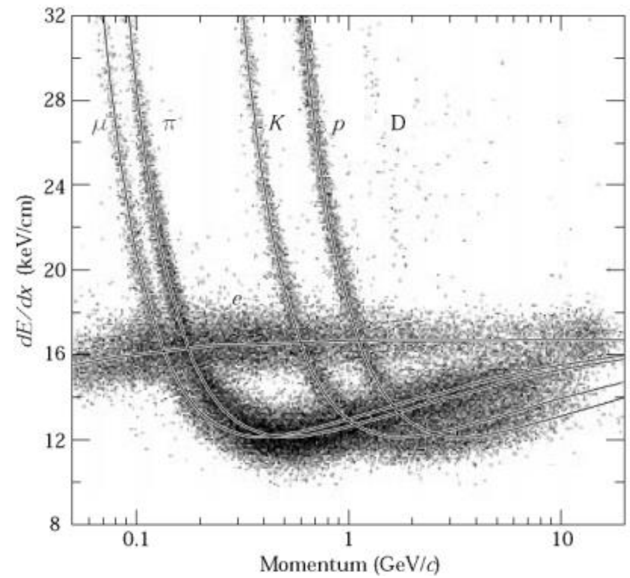


Energy loss depends on the particle velocity and is ≈ independent of the particle's mass M.

The energy loss as a function of particle Momentum P= Mcβγ IS however depending on the particle's mass

By measuring the particle momentum (deflection in the magnetic field) and measurement of the energy loss on can measure the particle mass

→ Particle Identification !



$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, Z_1^2 \frac{p^2 + M^2c^2}{p^2} N_A \frac{Z}{A}\left[\ln \frac{2m_e c^2 F}{I}\frac{p^2}{M^2c^2} - \frac{p^2}{p^2 + M^2c^2}\right]$$

Range of Particles in Matter

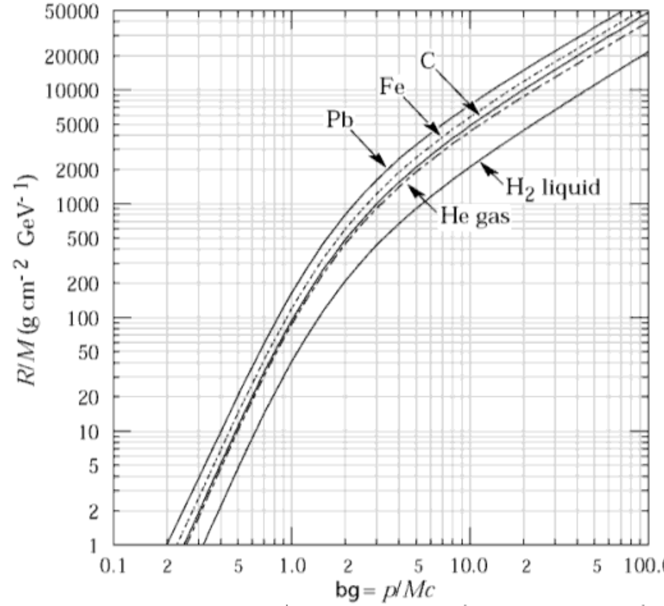
Particle of mass M and kinetic Energy E_0 enters matter and looses energy until it comes to rest at distance R.

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

$$R(\beta_0\gamma_0) = \frac{Mc^2}{\rho} \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

$$\frac{\rho}{Mc^2} R(\beta_0\gamma_0) = \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

≈Independent of the material

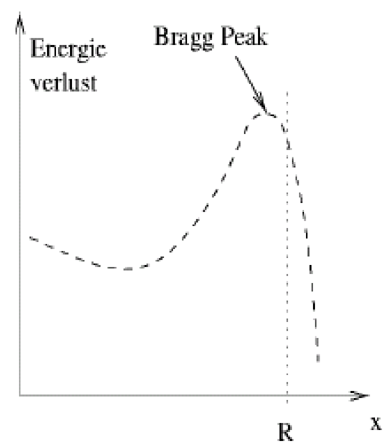


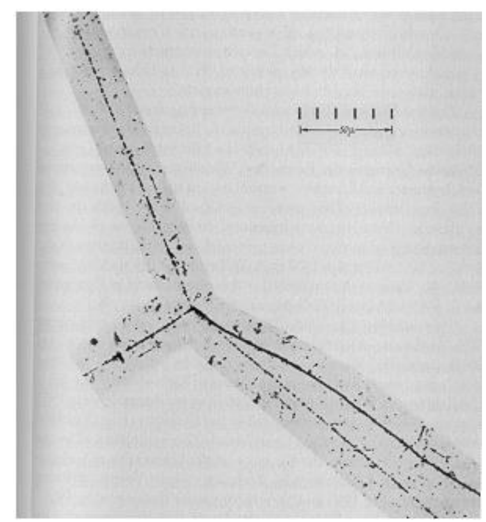
Bragg Peak:

For βγ>3 the energy loss is ≈ constant (Fermi Plateau)

If the energy of the particle falls below βγ=3 the energy loss rises as $1/\beta^2$

Towards the end of the track the energy loss is largest → Cancer Therapy.

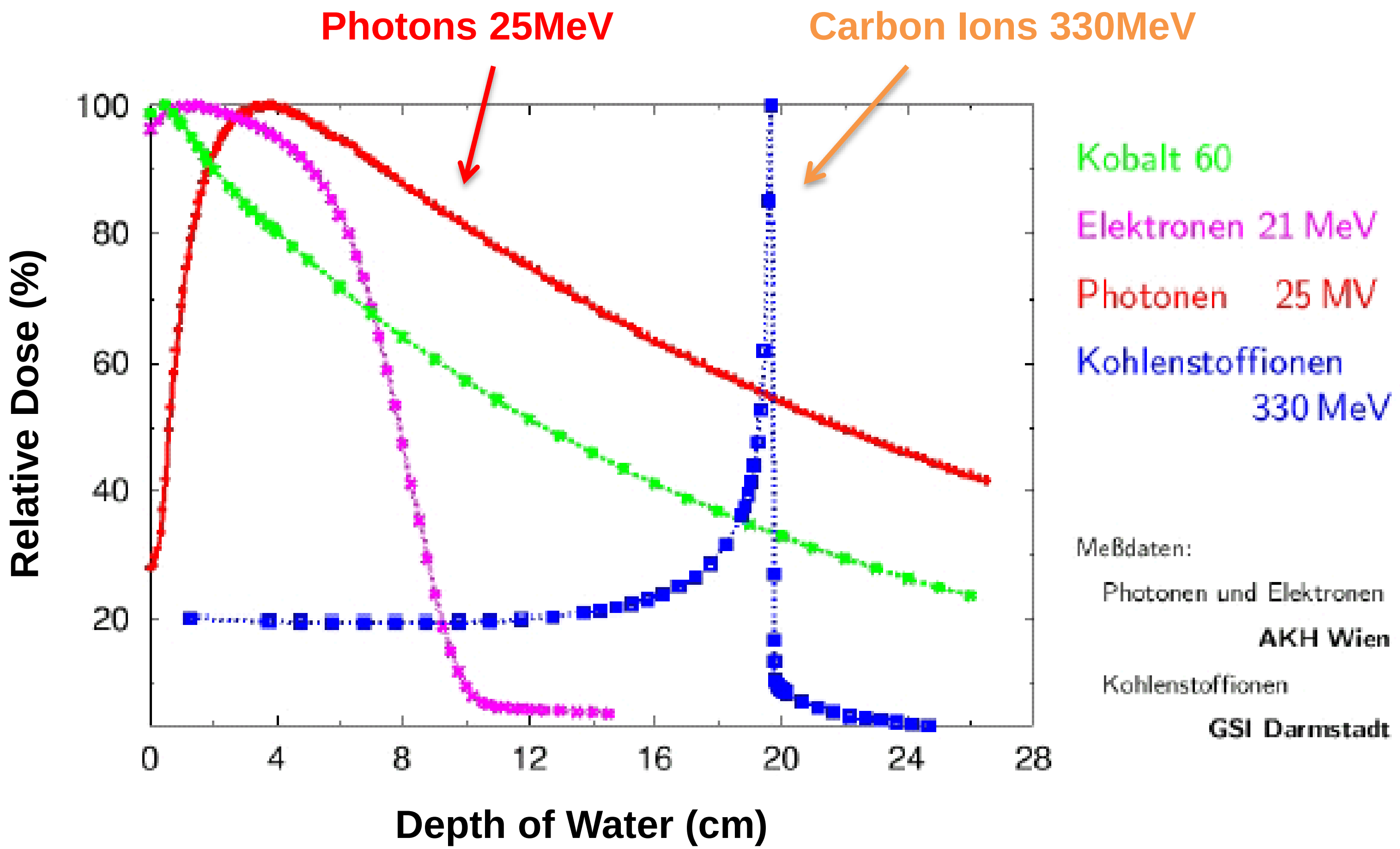




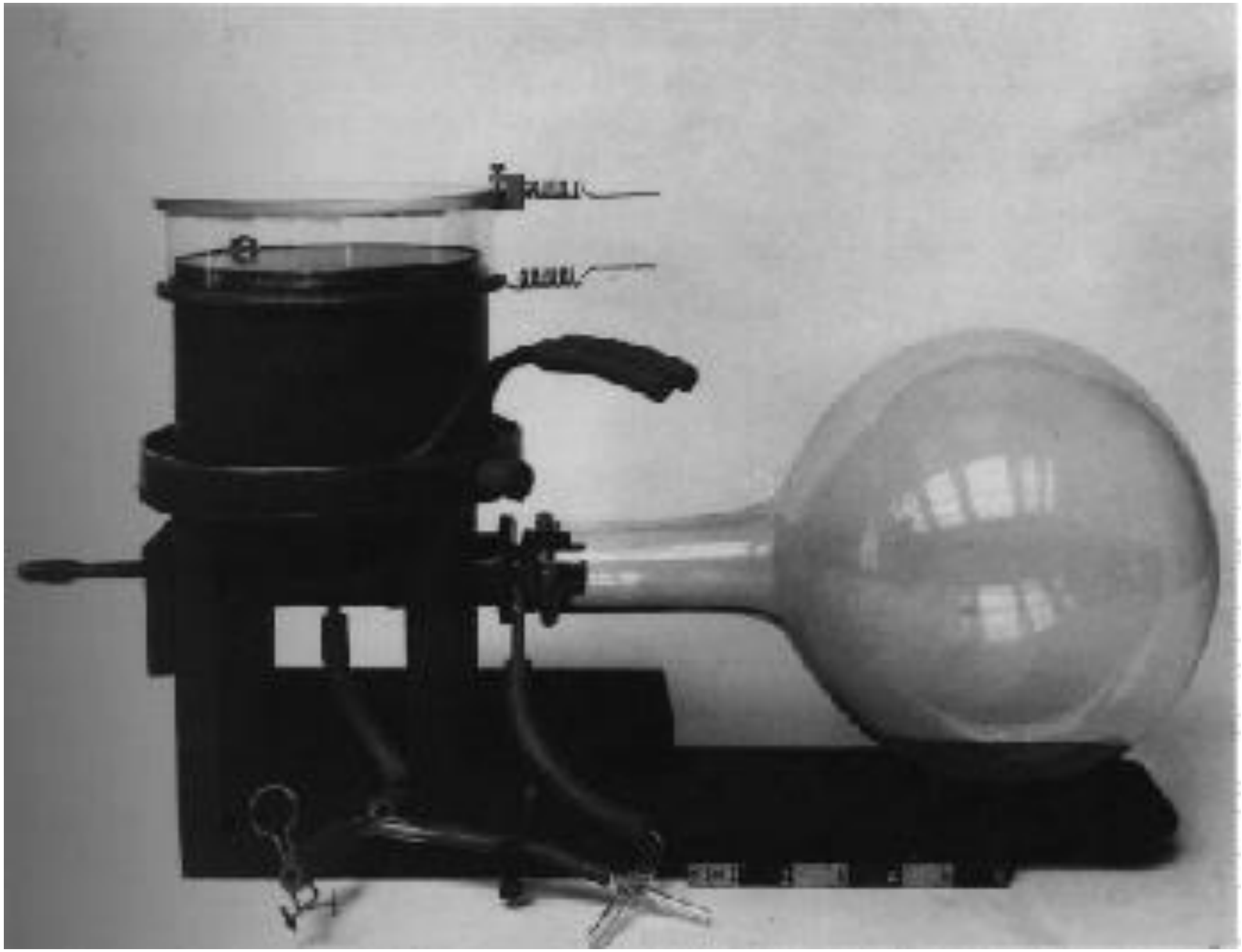
Range of Particles in Matter

Average Range:

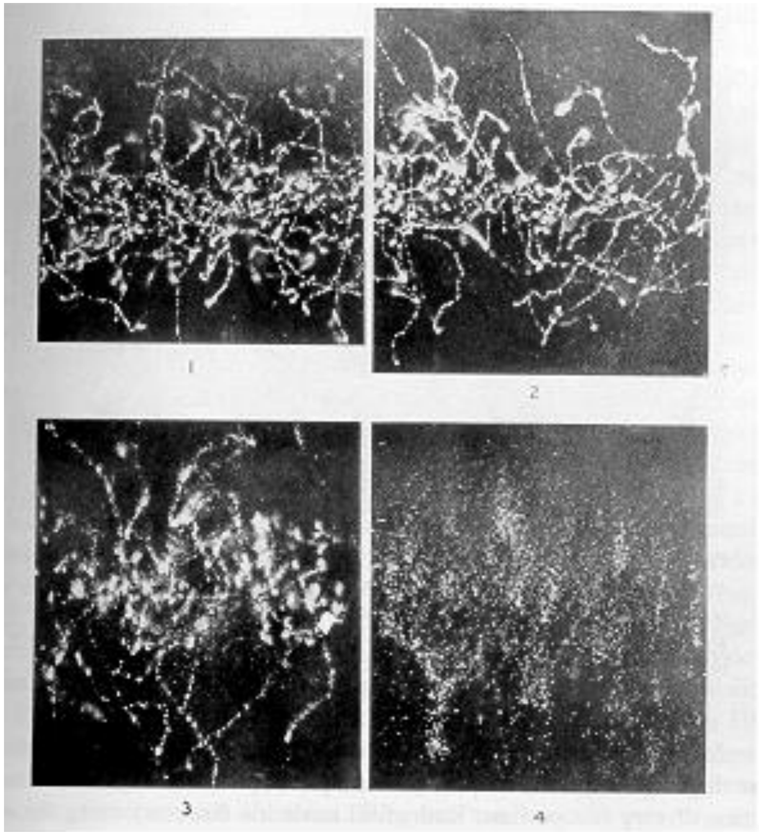
Towards the end of the track the energy loss is largest → Bragg Peak → Cancer Therapy

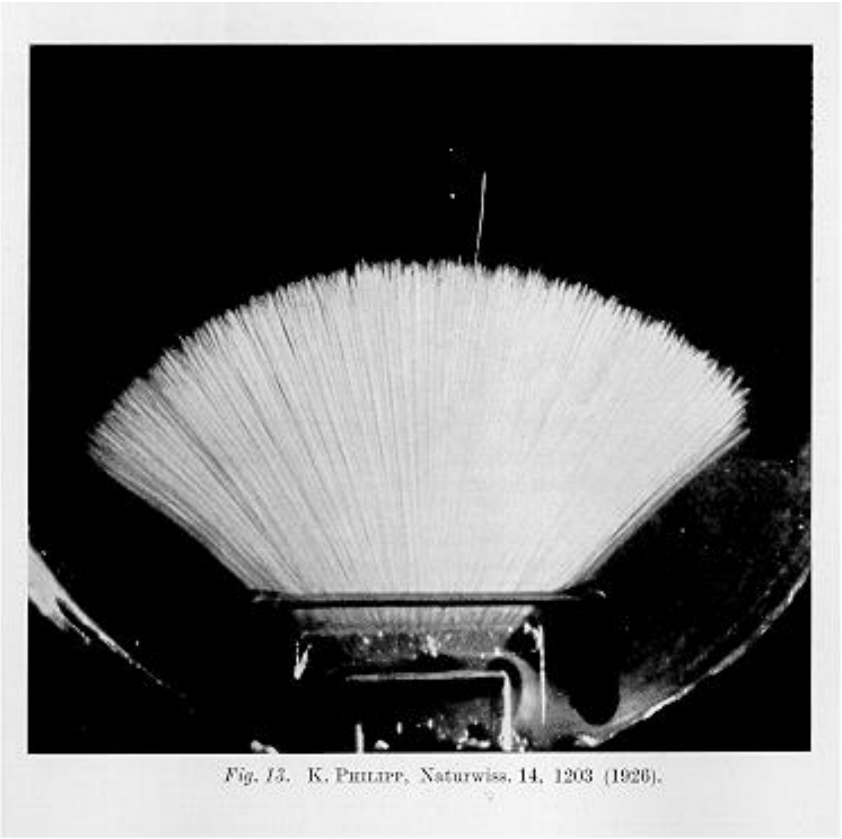


Мъглинна камера



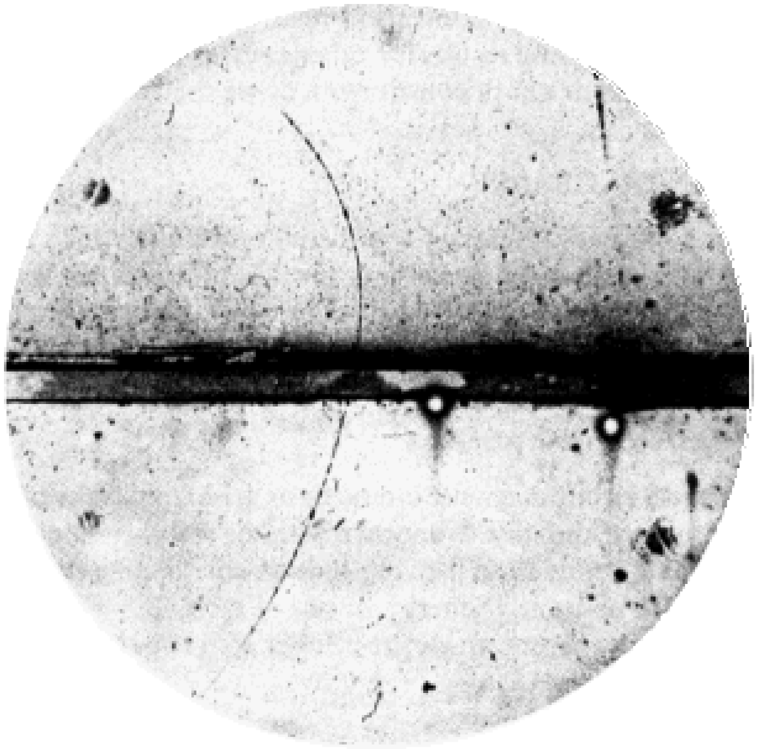
Wilson Cloud Chamber 1911





X-rays, Wilson 1912

Alphas, Philipp 1926

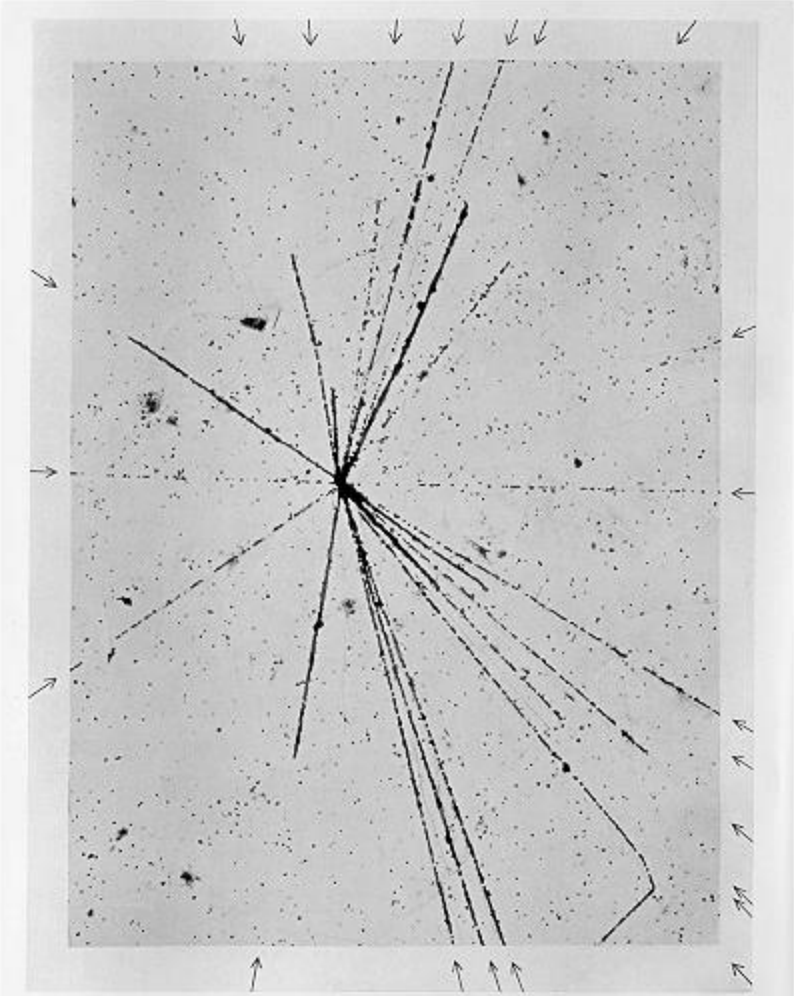


Positron discovery,
Carl Andersen 1933

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

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

Ядрени фотоемулсии



'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.

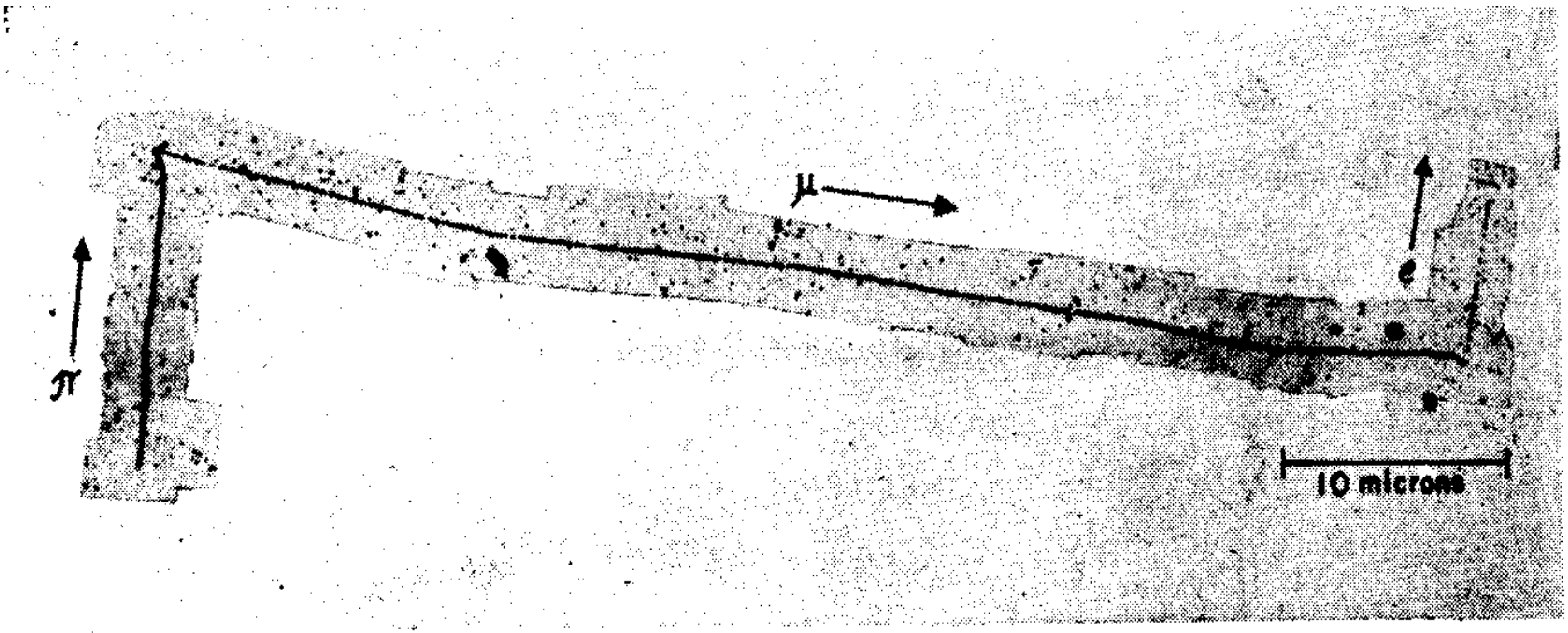


Fig. 4.8.2. Mosaic of microphotographs showing a $\pi \rightarrow \mu \rightarrow e$ decay. Kodak NT4 electron-sensitive emulsion. From Brown *et al.* (BRH49.2).

Мехурчеста камера

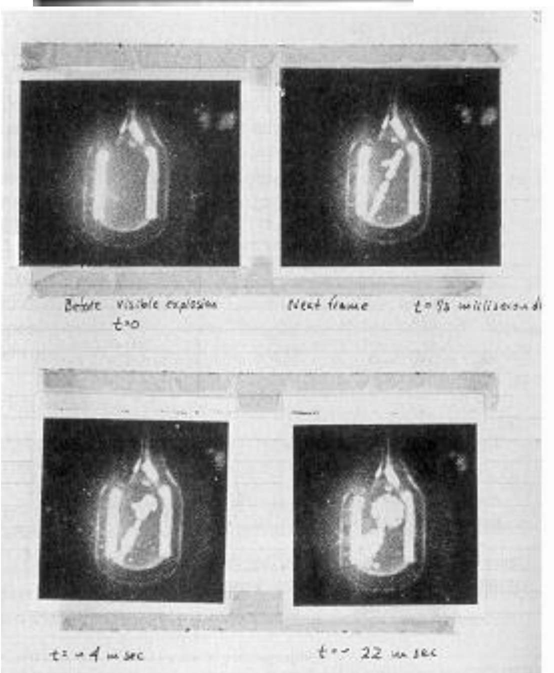


Figure 5.5 Bubble chamber movies (1952). Glaser first filmed distinct track

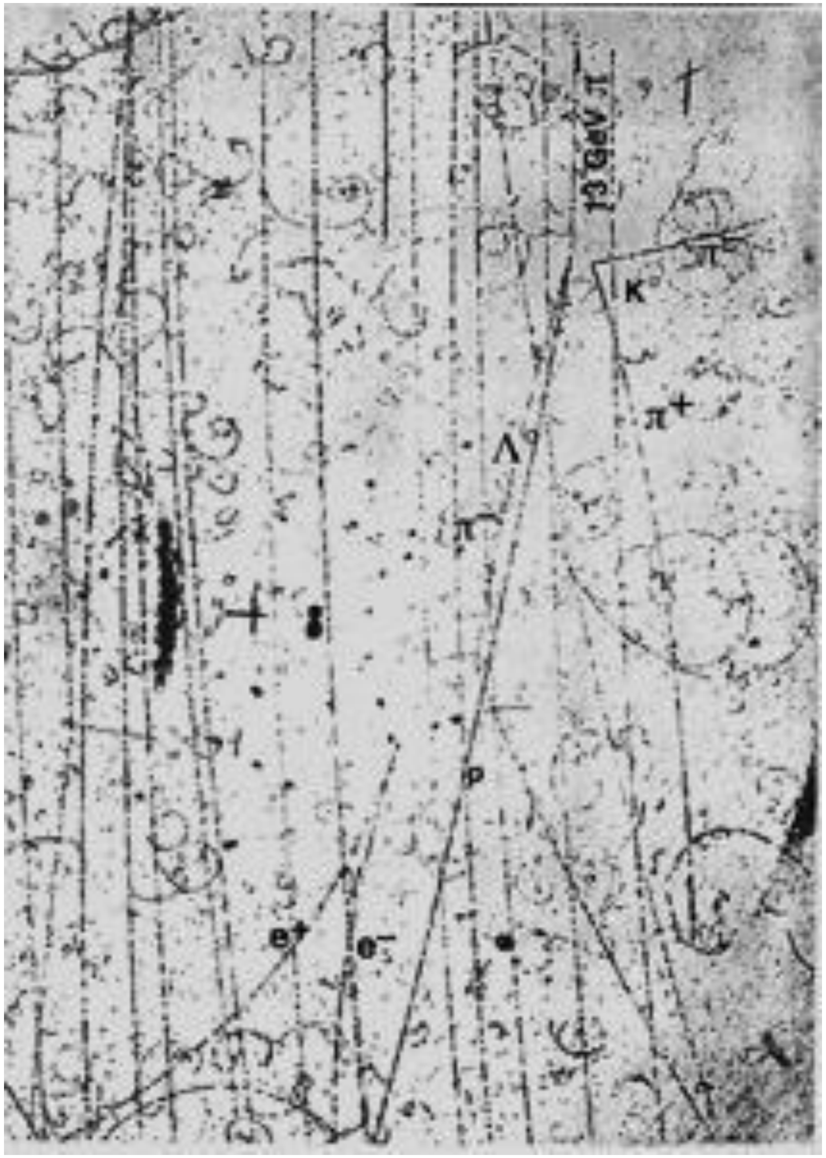
In the early 1950ies Donald Glaser tried to build on the cloud chamber analogy:

Instead of supersaturating a gas with a vapor 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**

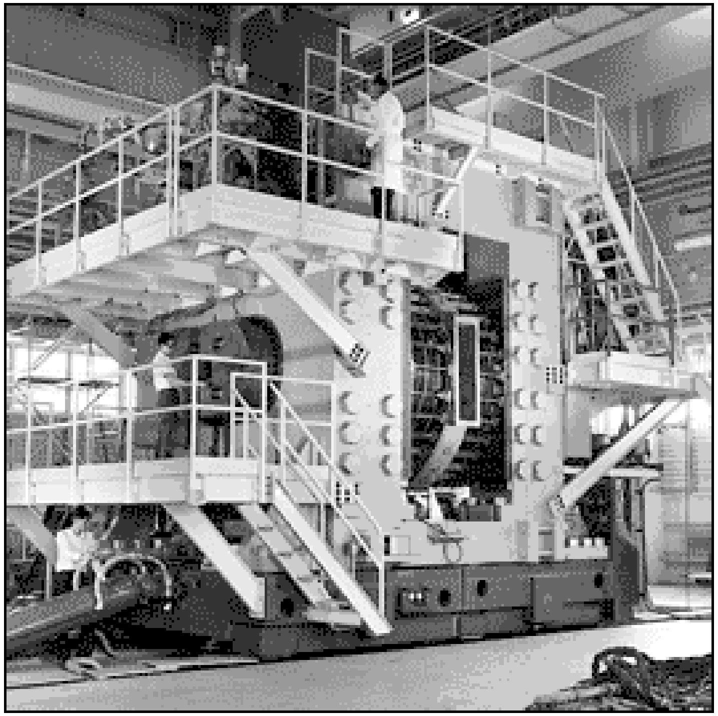


In the bubble chamber, with a density about 1000 times larger that the cloud chamber, the liquid acts as the target and the detecting medium.

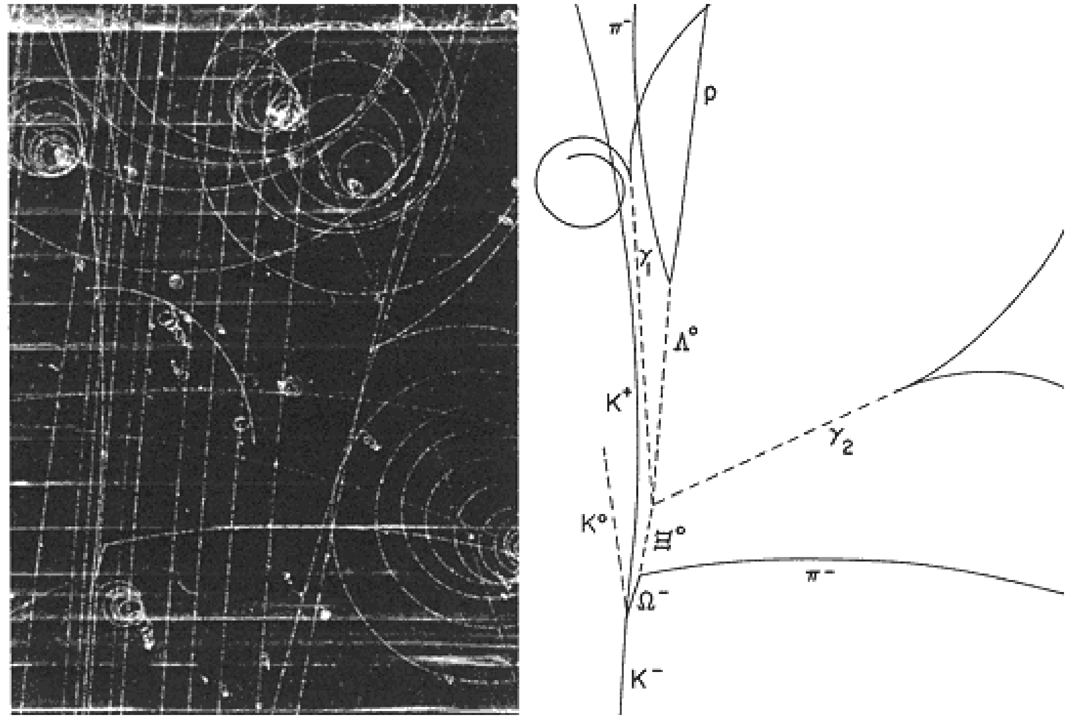
Figure:
A propane chamber with a magnet discovered the $\Sigma°$ in 1956.

A 1300 MeV negative pion hits a proton to produce a neutral kaon and a $\Sigma°$, which decays into a $\Lambda°$ and a photon.

The latter converts into an electron-positron pair.

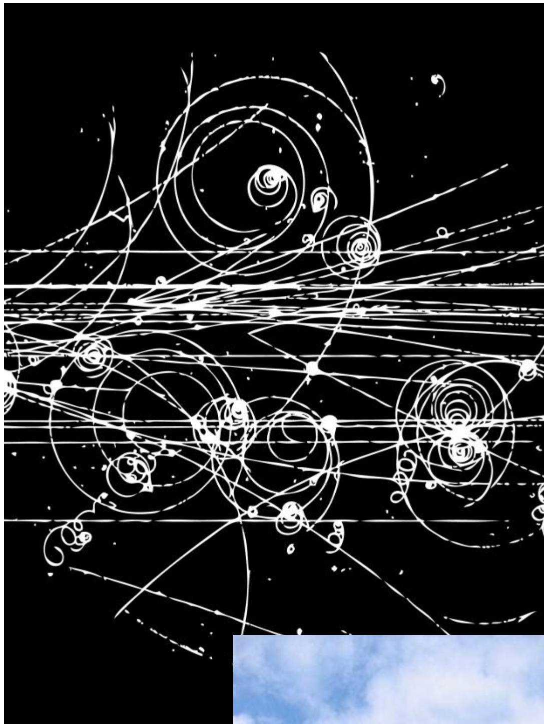


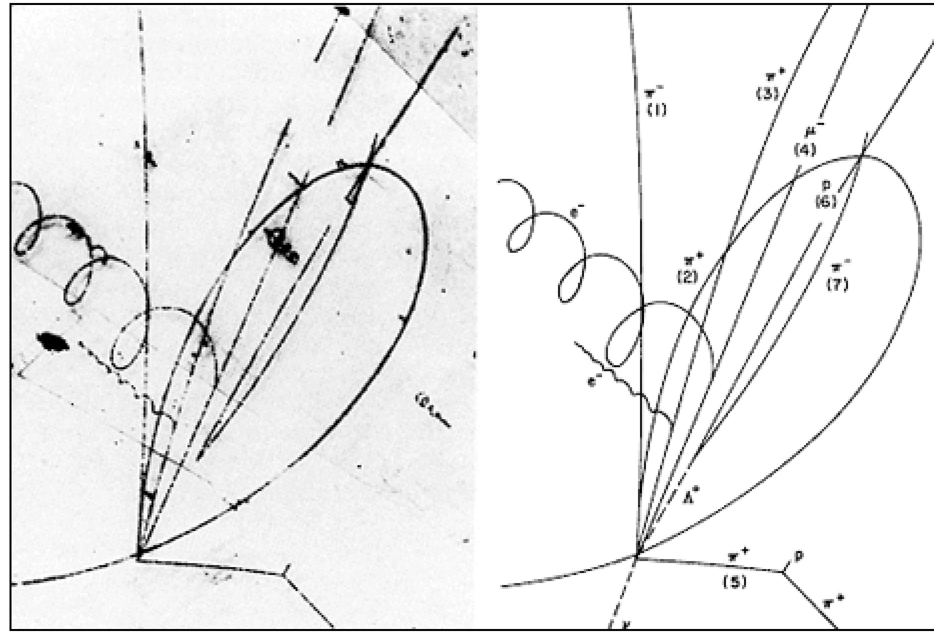
The 80-inch Bubble Chamber



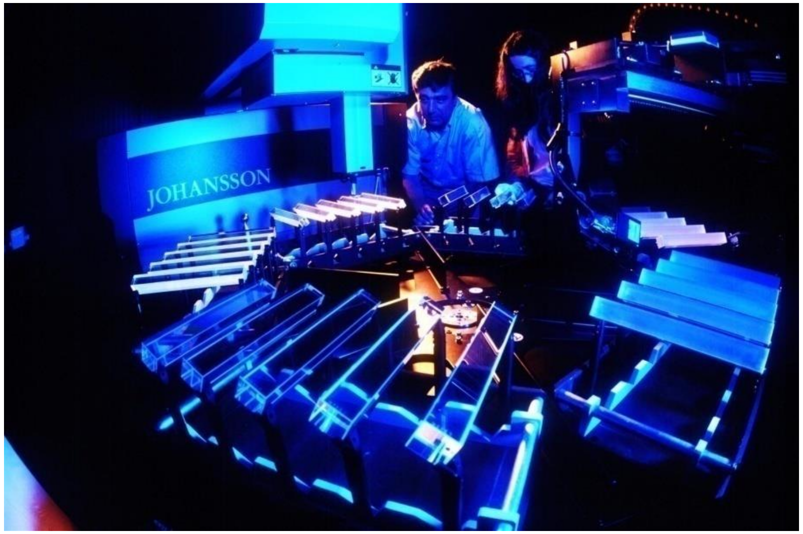
BNL, First Pictures 1963, 0.03s cycle

Discovery of the Ω^- in 1964

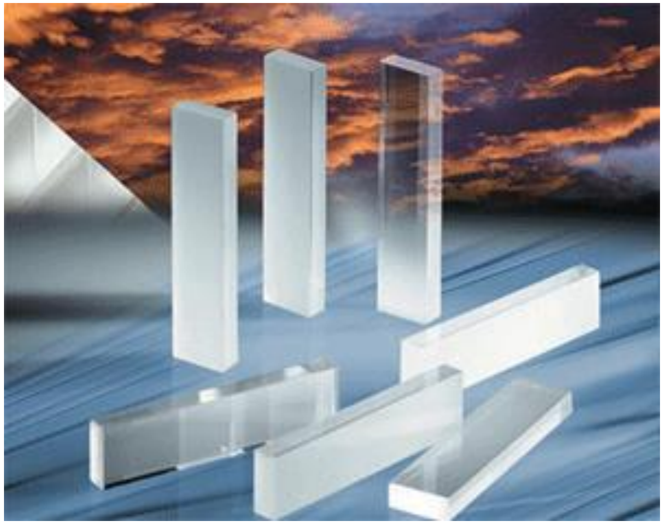




The discovery of the [Σ^{++}_c baryon] was made in a bubble chamber at the [Brookhaven National Laboratory] in 1974.



Detectors based on registration of excited atoms → Scintillators



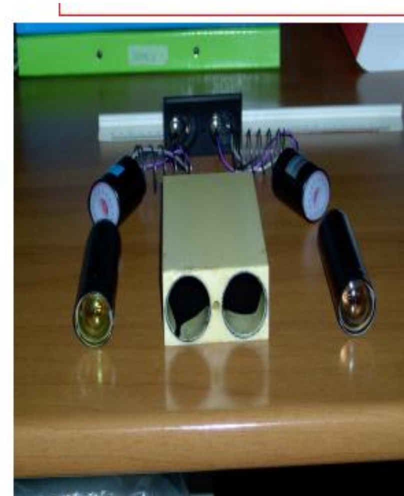
Световоди

Readout: Light guides

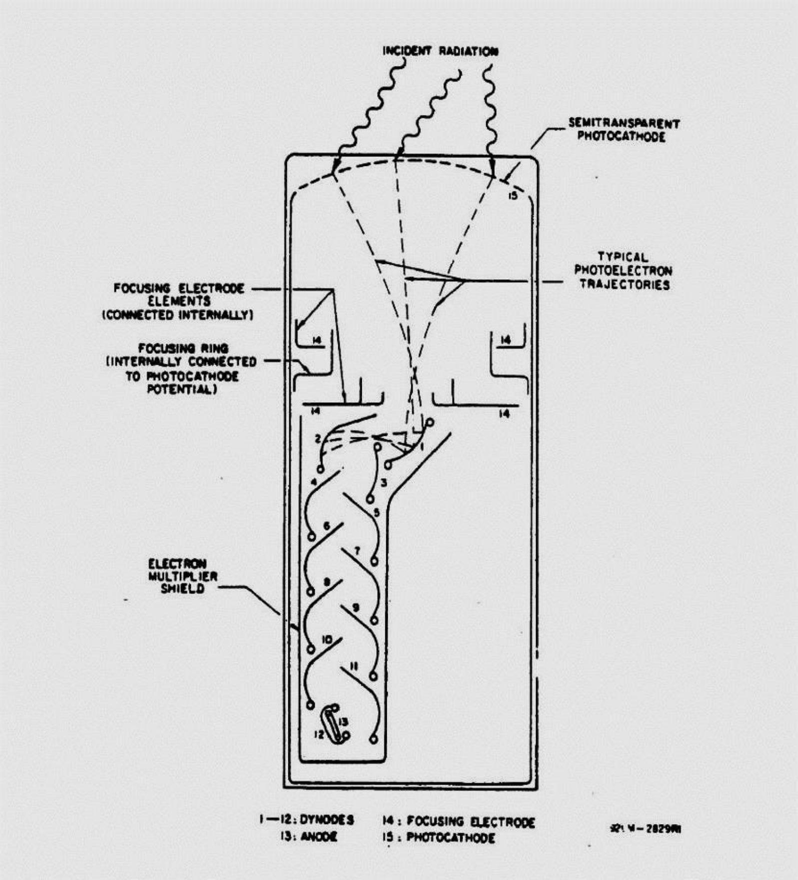
$3.5 \times 3.5\ cm^2$

$4 \times 4\ cm^2$

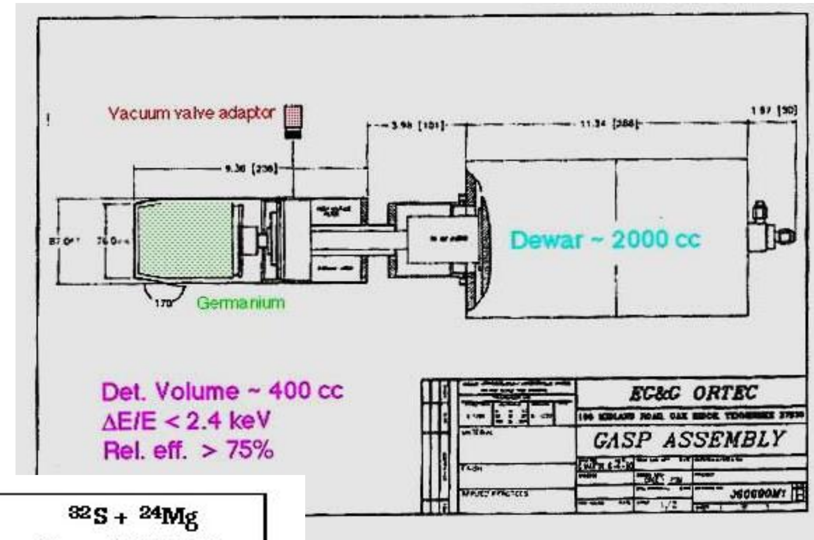
$4 \times 2.5\ cm^2$

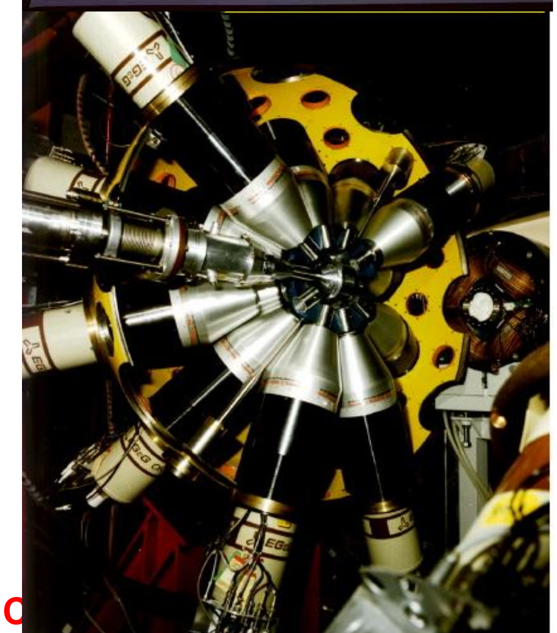


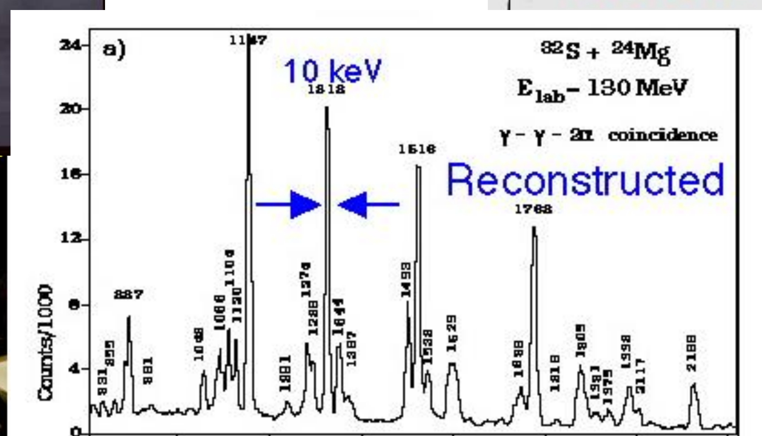
Фотоумножители



Полупроводникови детектори – планарни (за заредени частици), обемни (за γ-кванти



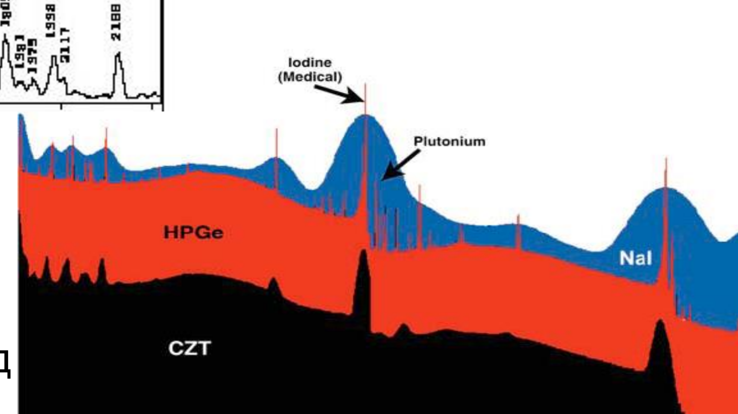




Натриев йодид

Свръх чист германий

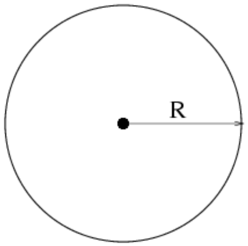
Кадмиево-цинков телурид



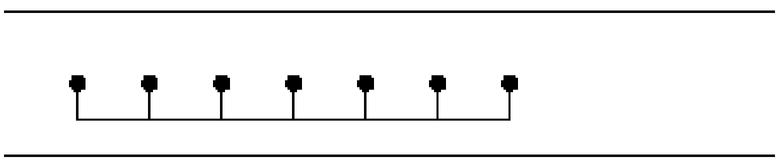
Многонишкови пропорционални камери

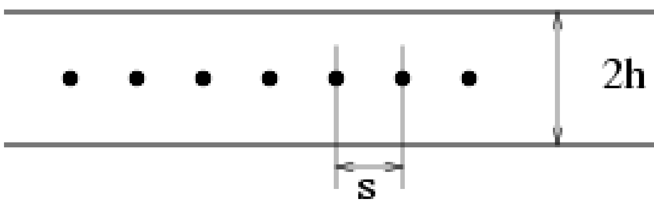
G. Charpak invented in 1968 the
Multi Wire Proportional Chamber:
readout of individual wires and
proportional mode working point.

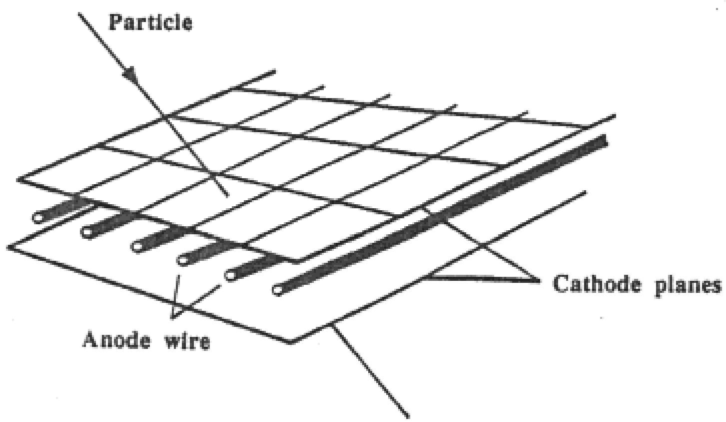
Tube, Geiger- Müller, 1928

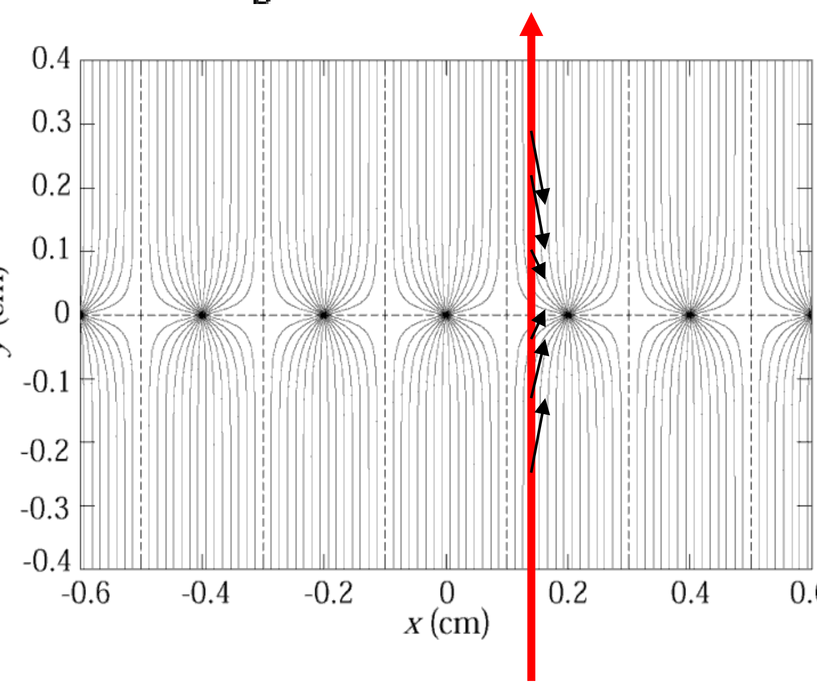


Multi Wire Geometry, in H. Friedmann 1949

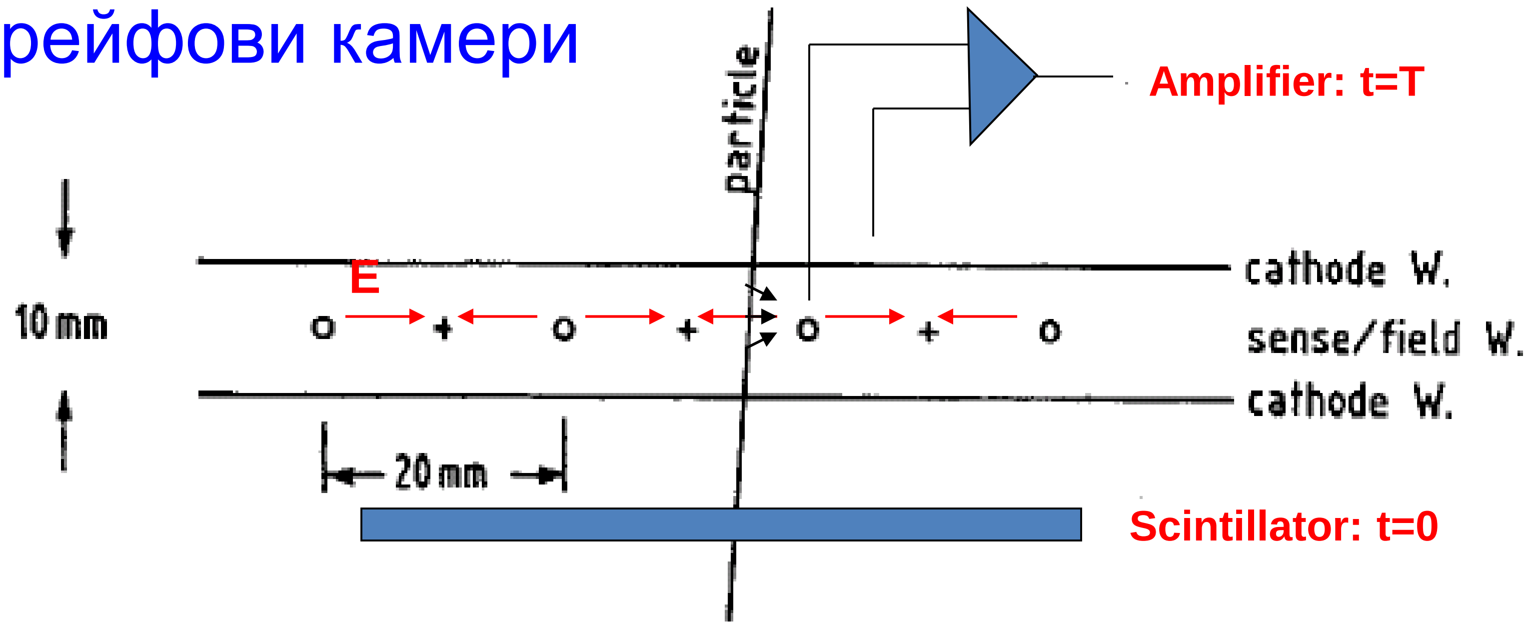








Дрейфови камери



In an alternating sequence of wires with different potentials one finds an electric field between the 'sense wires' and 'field wires'.

The electrons are moving to the sense wires and produce an avalanche which induces a signal that is read out by electronics.

The time between the passage of the particle and the arrival of the electrons at the wire is measured.

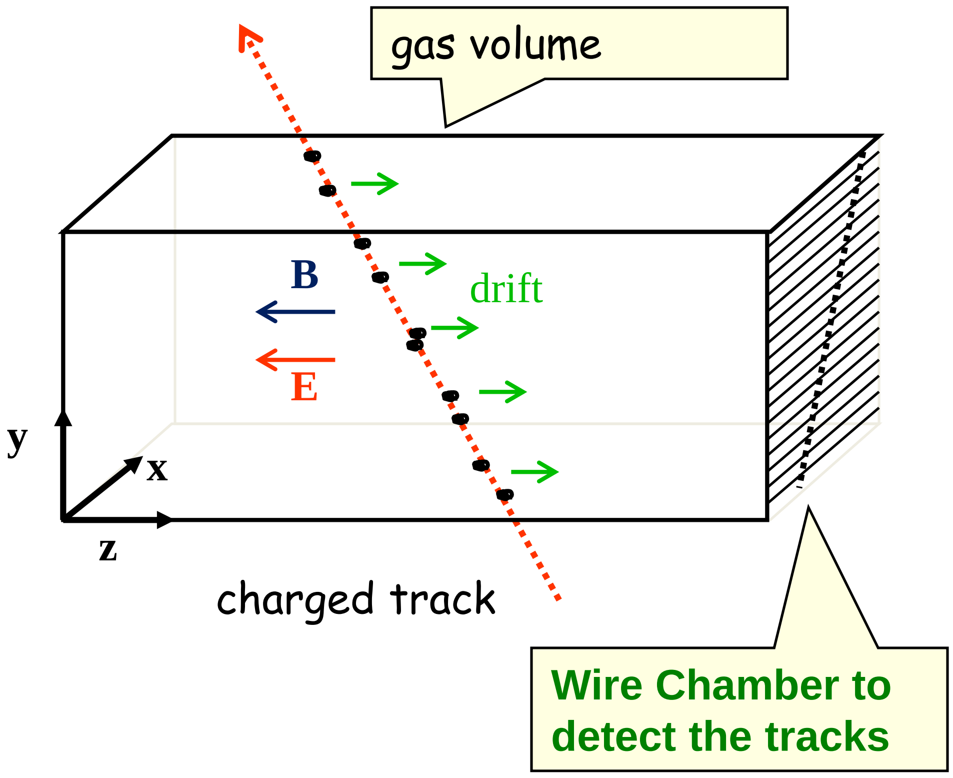
The drift time T is a measure of the position of the particle !

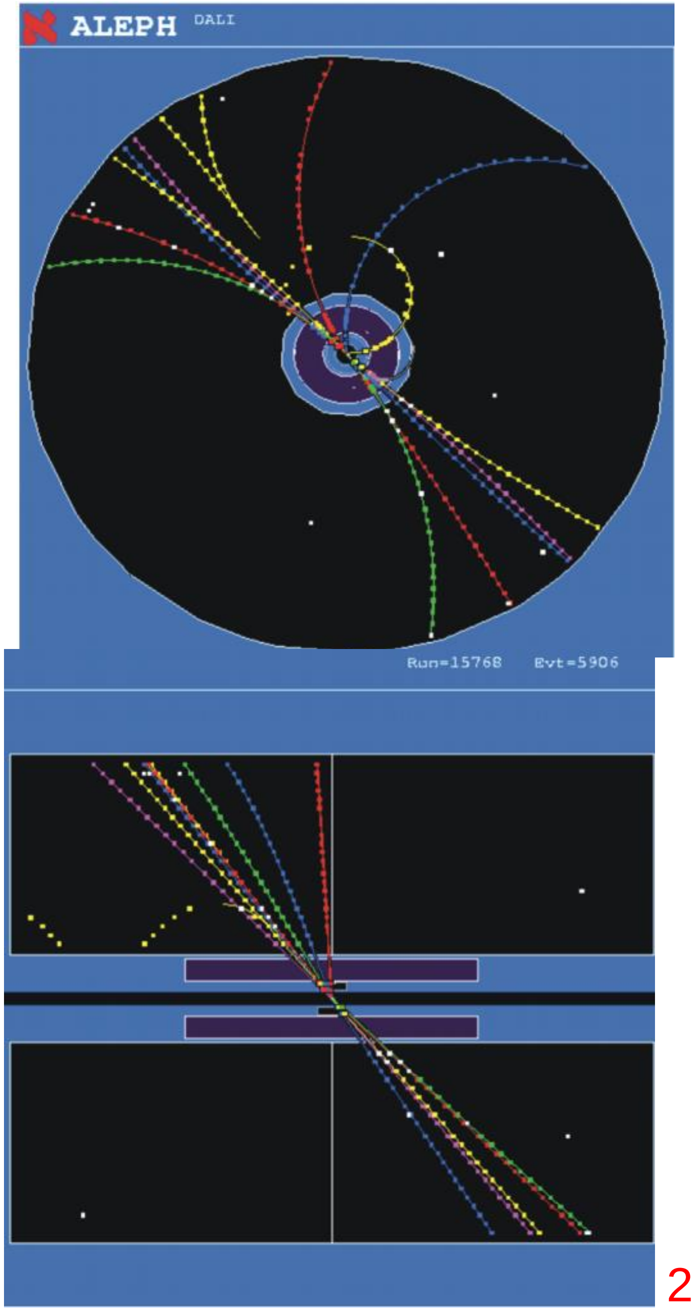
By measuring the drift time, the wire distance can be increased (compared to the Multi Wire Proportional Chamber) → save electronics channels !

Времепроекционна камера (Time Projection Chamber: TPC)

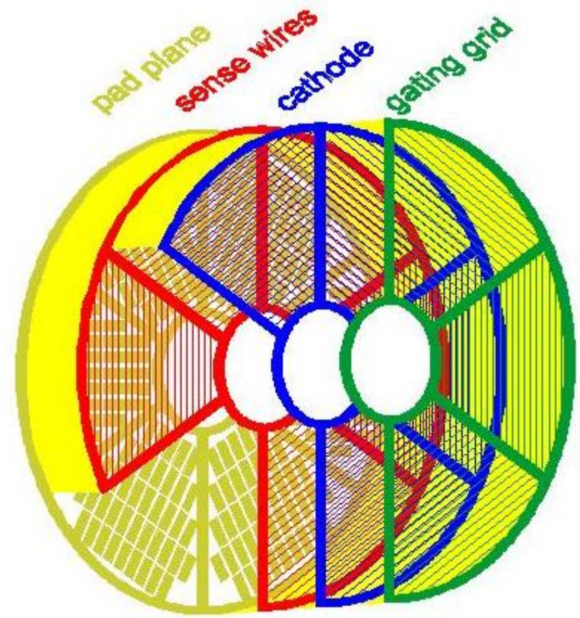
Gas volume with parallel E and B Field.
B for momentum measurement. Positive effect:
Diffusion is strongly reduced by E//B (up to a factor 5).

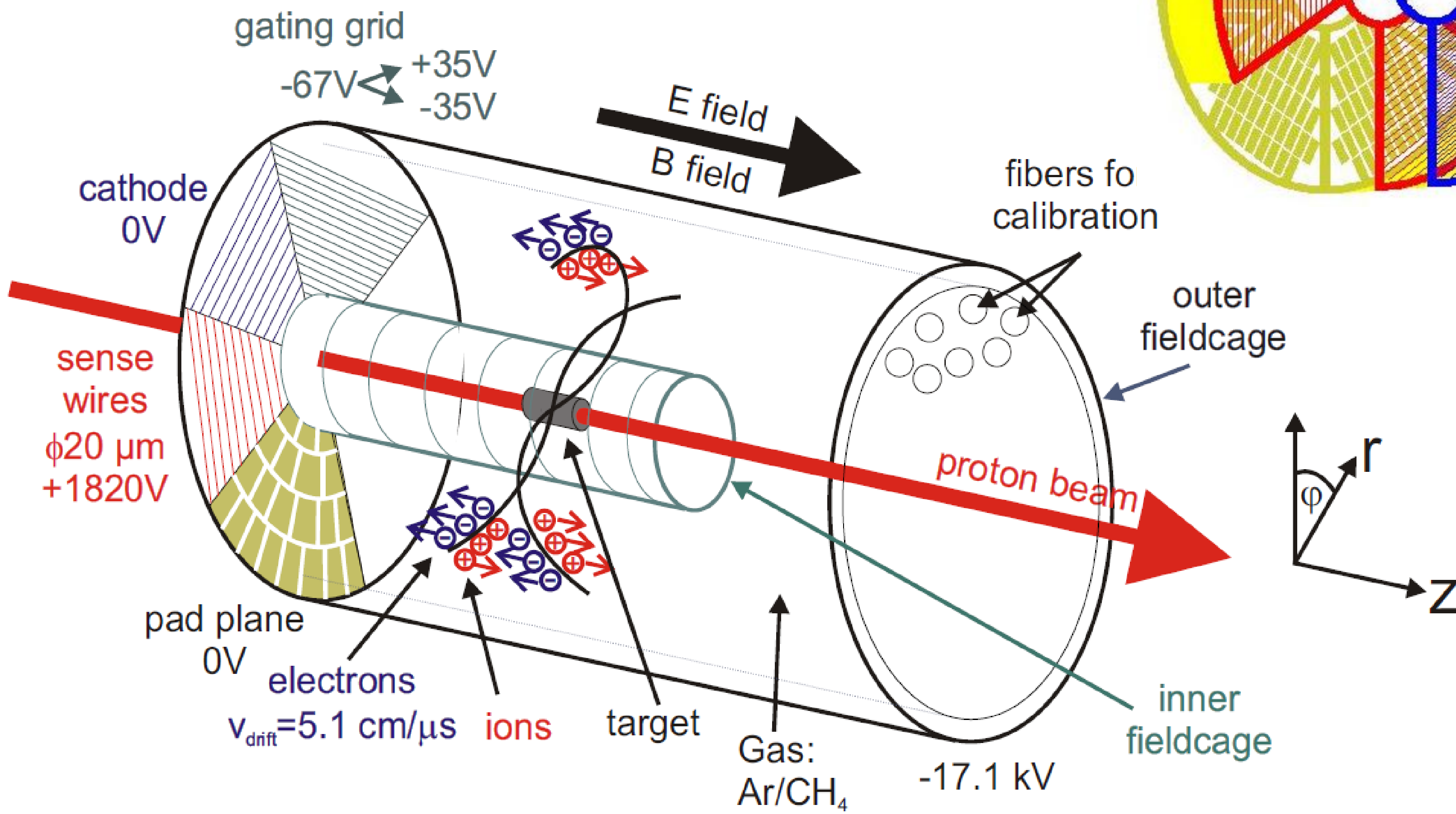
Drift Fields 100-400V/cm. Drift times 10-100 μs.
Distance up to 2.5m !





Времепроекционна камера
(Time Projection Chamber: TPC)



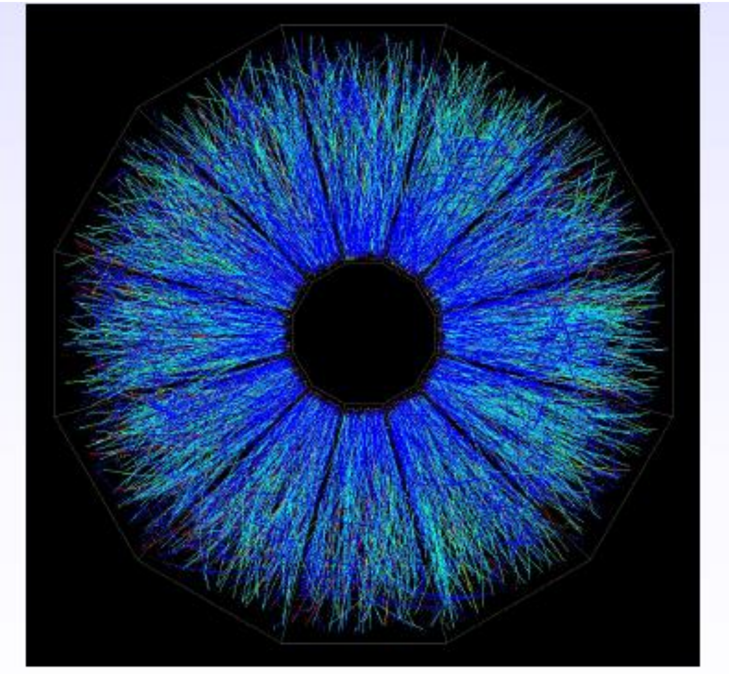


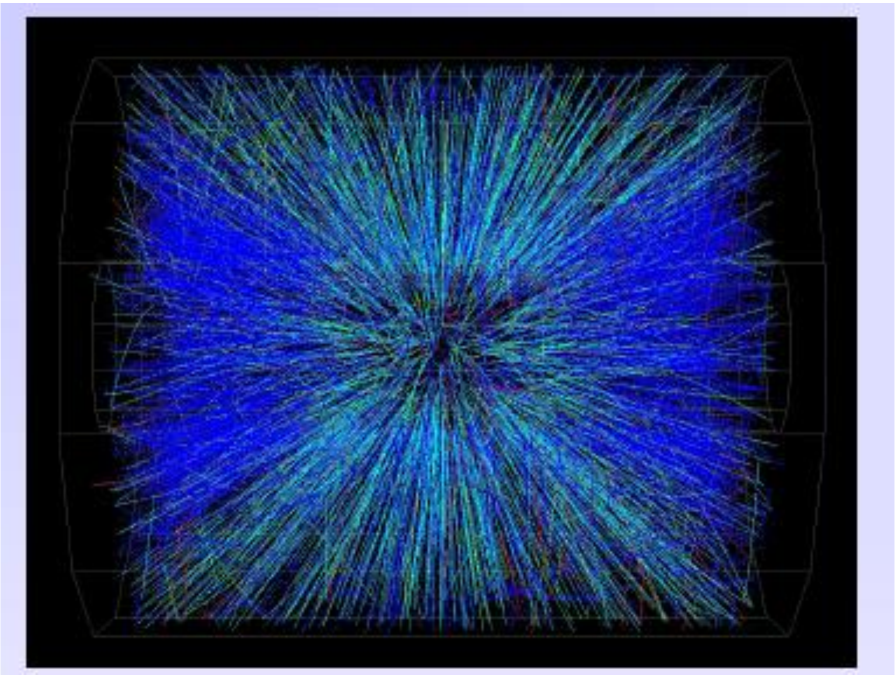
STAR TPC (BNL)

Event display of a Au Au collision at CM energy of 130 GeV/n.

Typically around 200 tracks per event.

Great advantage of a TPC: The only material that is in the way of the particles is gas → very low multiple scattering → very good momentum resolution down to low momenta !

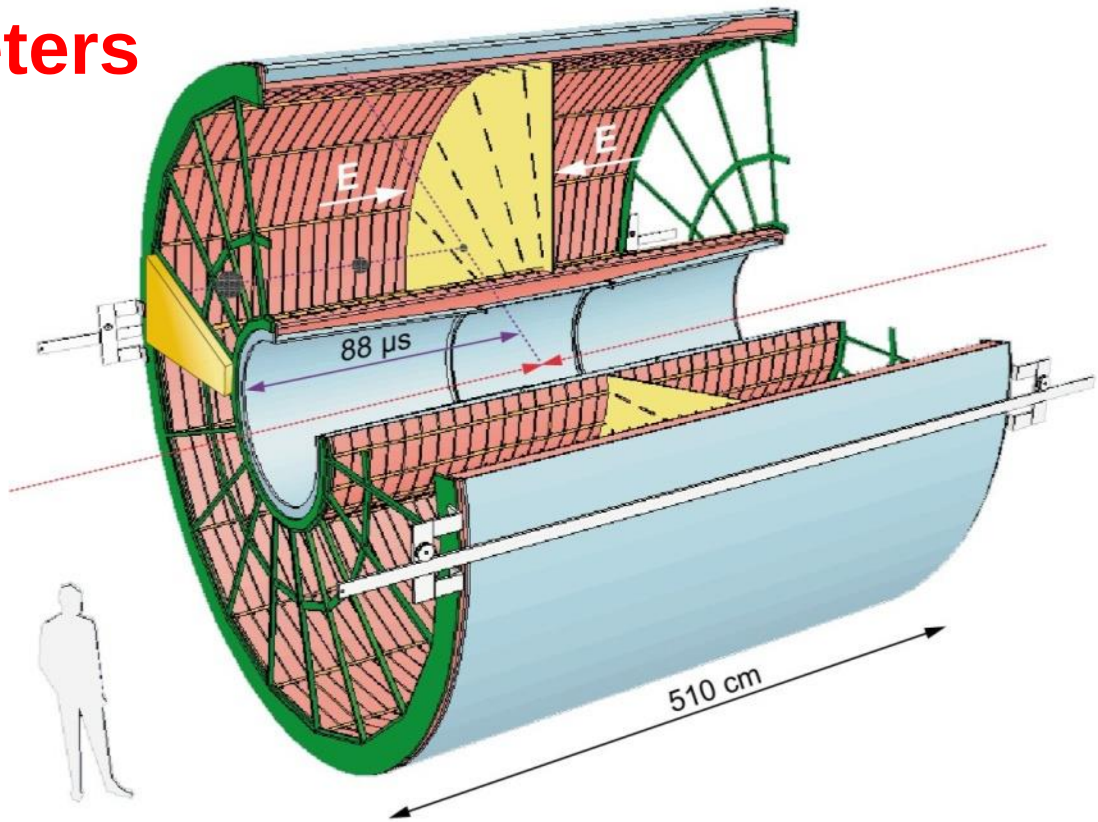




ALICE TPC: Parameters

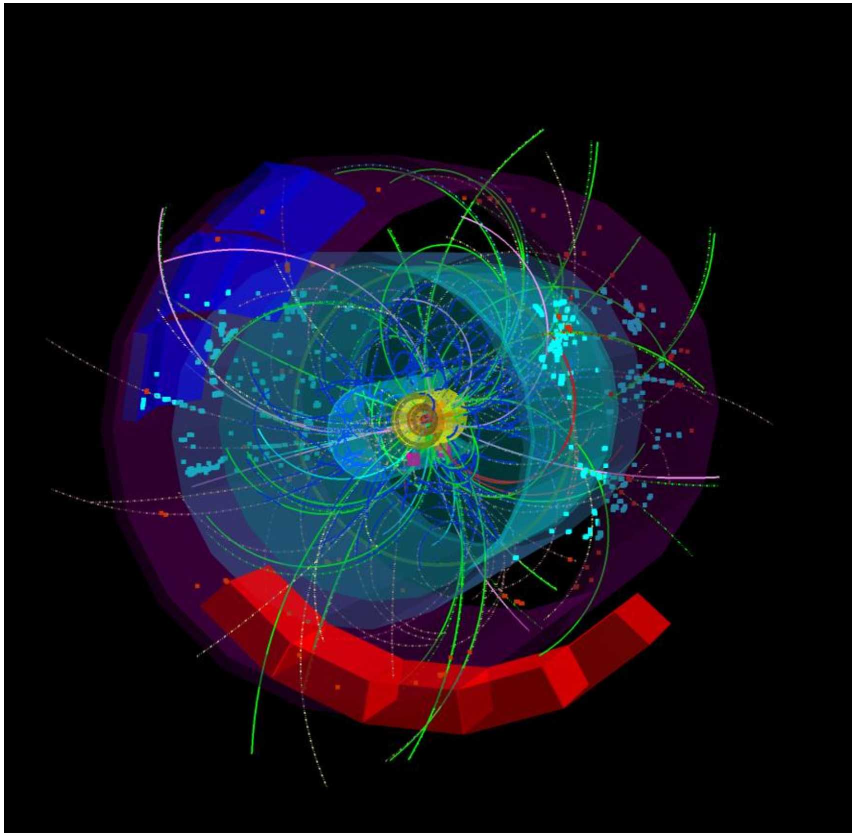
- Largest TPC:
  - Length 5m
  - Diameter 5m
  - Volume $88 m^3$
  - Detector area $32 m^2$
  - Channels ~570 000
- High Voltage:
  - Cathode -100kV
- Material X_0
  - Cylinder from composite materials from airplane

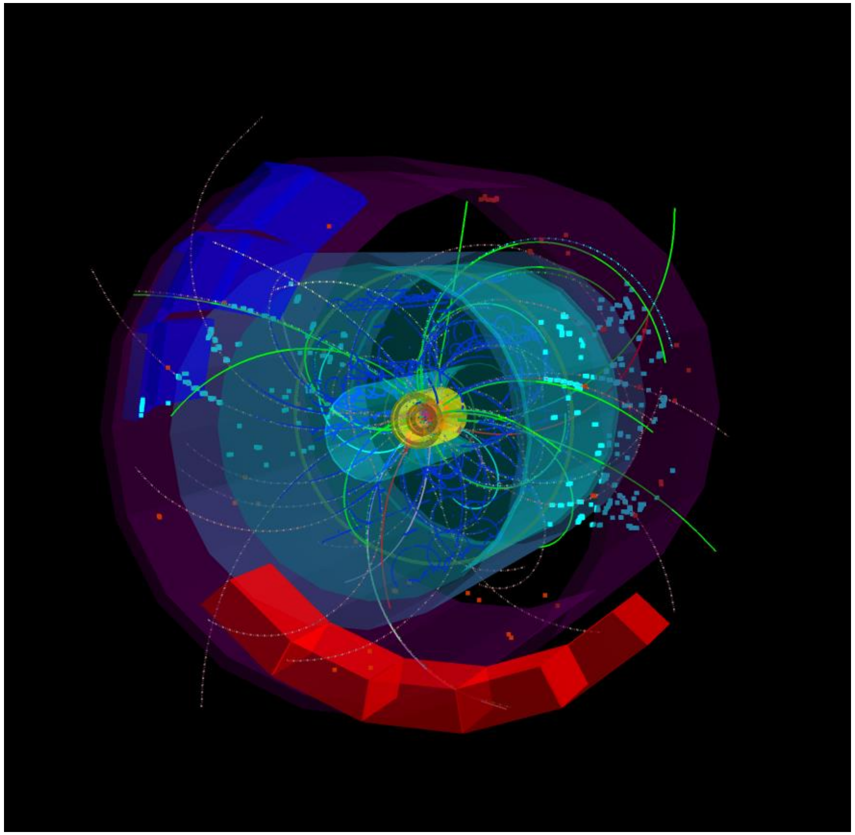
    industry (X_0= ~3%)



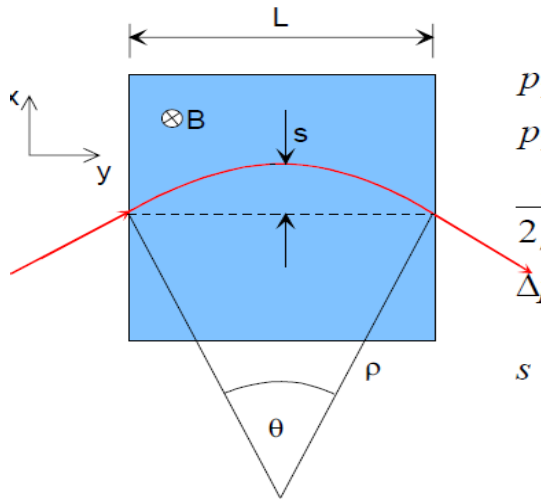
- Gas Ne/ CO_2 90/10%
- Field 400V/cm
- Gas gain $>10^4$
- Position resolution σ= 0.25mm
- Diffusion: σ_t= 250μm
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T

First 7 TeV Collisions in the ALICE TPC in March 2010.





Momentum measurement



$$p_T = qB\rho$$

$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L\cdot B}{p_T}$$

$$\Delta p_T = p_T \sin\theta \approx 0.3L\cdot B$$

$$s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

the sagitta s is determined by 3 measurements with error $\sigma(x)$: $s = x_2 - \frac{x_1 + x_3}{2}$

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}$$

for N equidistant measurements, one obtains

(R.L. Gluckstern, NIM 24 (1963) 381)

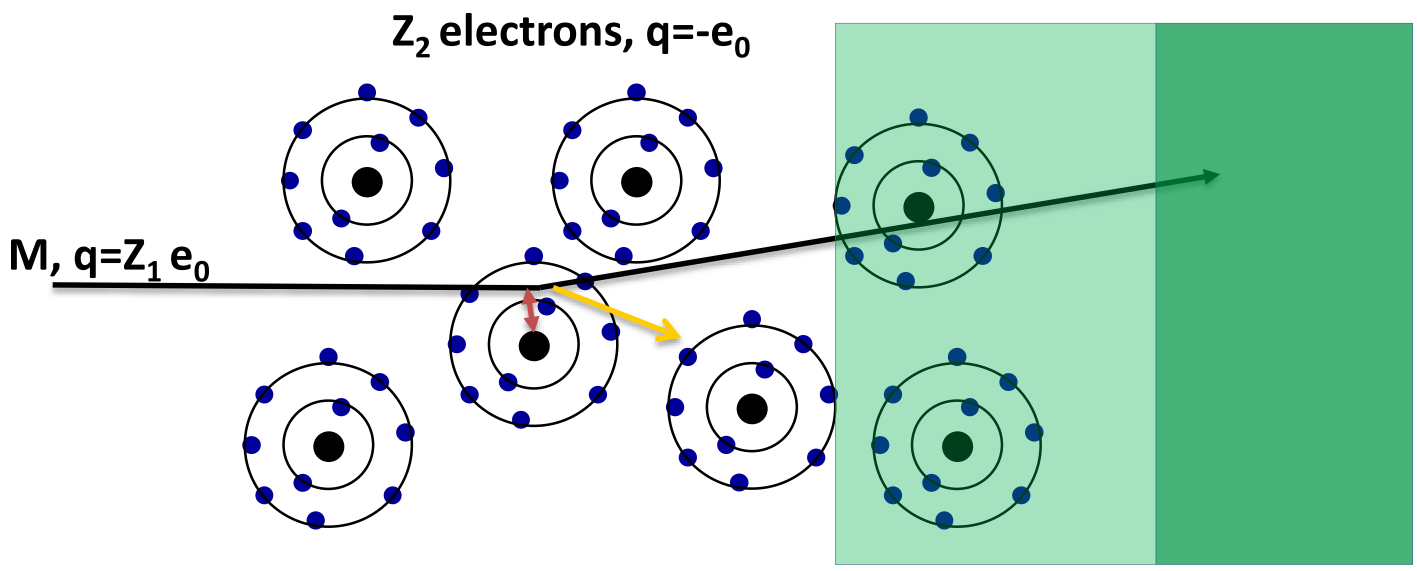
$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for } N \geq \approx 10\text{)}$$

ex: p_T=1 GeV/c, L=1m, B=1T, $\sigma(x)$=200μm, N=10

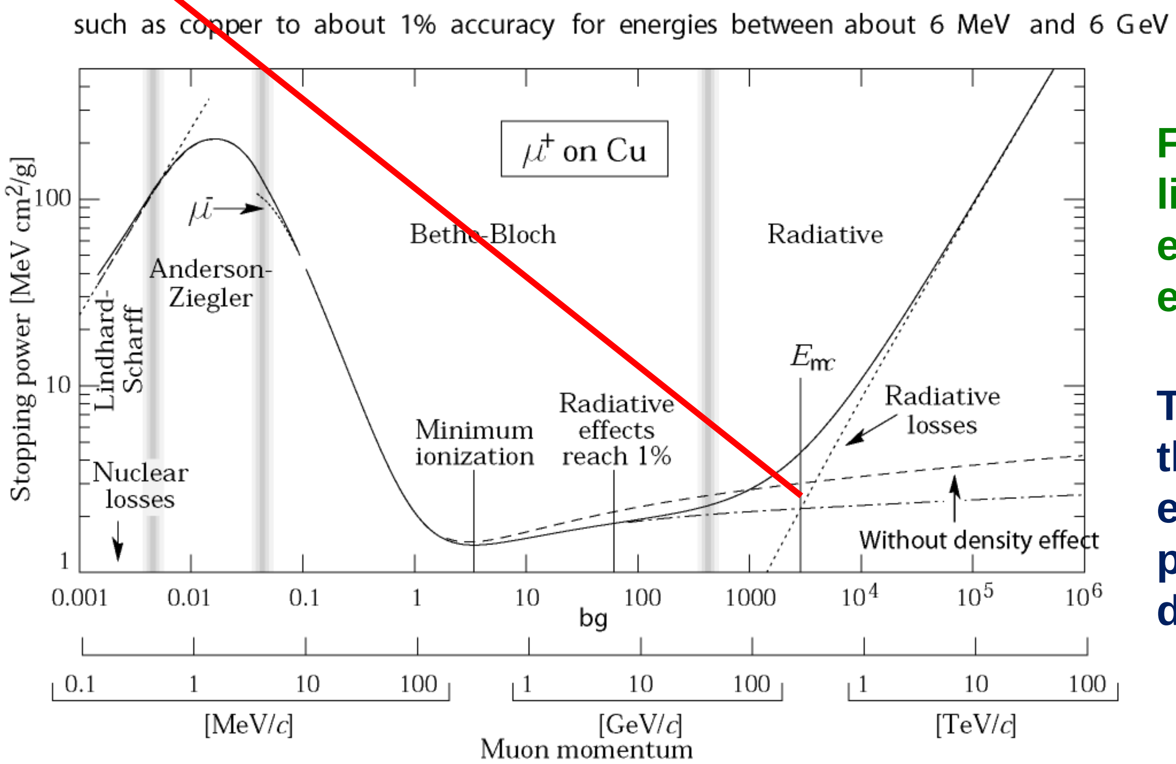
$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\% \qquad (s \approx 3.75\ \mathrm{cm})$$

Спирачно лъчение (bremsstrahlung)

A charged particle of mass M and charge $q=Z_1e$ is deflected by a nucleus of charge Ze which is partially 'shielded' by the electrons. During this deflection the charge is 'accelerated' and it therefore radiated → Bremsstrahlung.



Критична енергия



Electron Momentum 5 50 500 MeV/c

For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

Critical Energy: If dE/dx (Ionization) = dE/dx (Bremsstrahlung)

Muon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Critical energy E_c

$$\frac{dE}{dx}(E_c)\bigg|_{Brems} = \frac{dE}{dx}(E_c)\bigg|_{ion}$$

For electrons one finds approximately:

$$E_c^{solid+liq} = \frac{610MeV}{Z+1.24} \qquad E_c^{gas} = \frac{710MeV}{Z+1.24}$$

density effect of dE/dx(ionisation) !

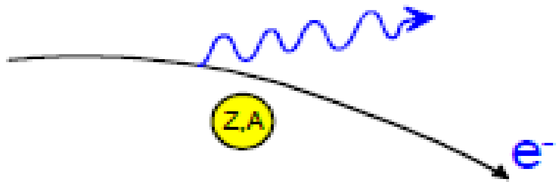
$E_c(e^-)$ in Fe(Z=26) = 22.4 MeV

For muons

$$E_c \approx E_c^{elec}\left(\frac{m_\mu}{m_e}\right)^2$$

$E_c(\mu)$ in Fe(Z=26) $\approx$ 1 TeV

Energy loss by Bremsstrahlung



Radiation of real photons in the Coulomb field of the nuclei of the absorber

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

Effect plays a role only for e± and ultra-relativistic μ (>1000 GeV)

For electrons:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}}$$

$$\boxed{-\frac{dE}{dx} = \frac{E}{X_0}}$$

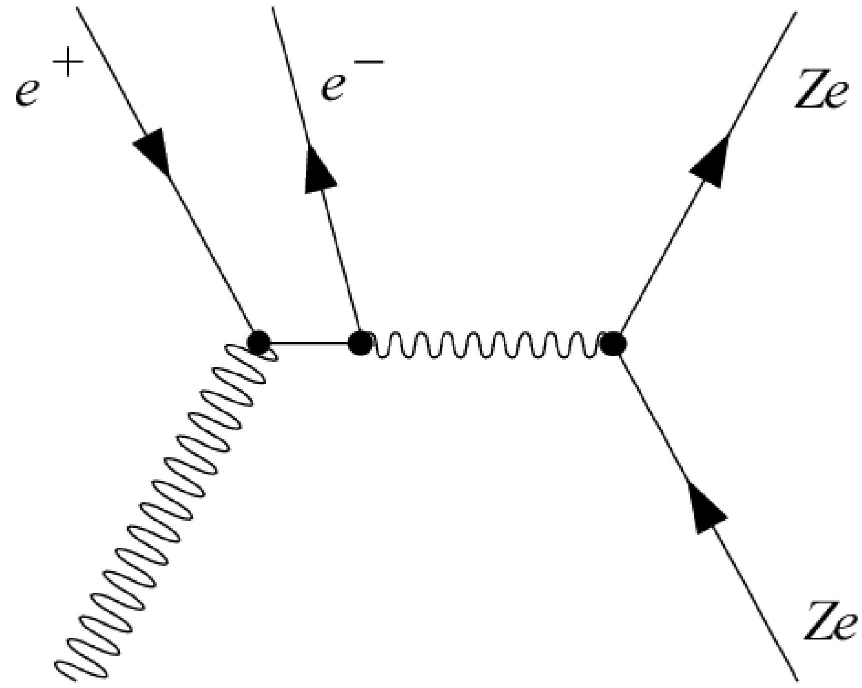
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

radiation length [g/cm²]

Раждане на двойка e^+e^- (Pair production)

Creation of an electron/positron pair in the field of an atom.

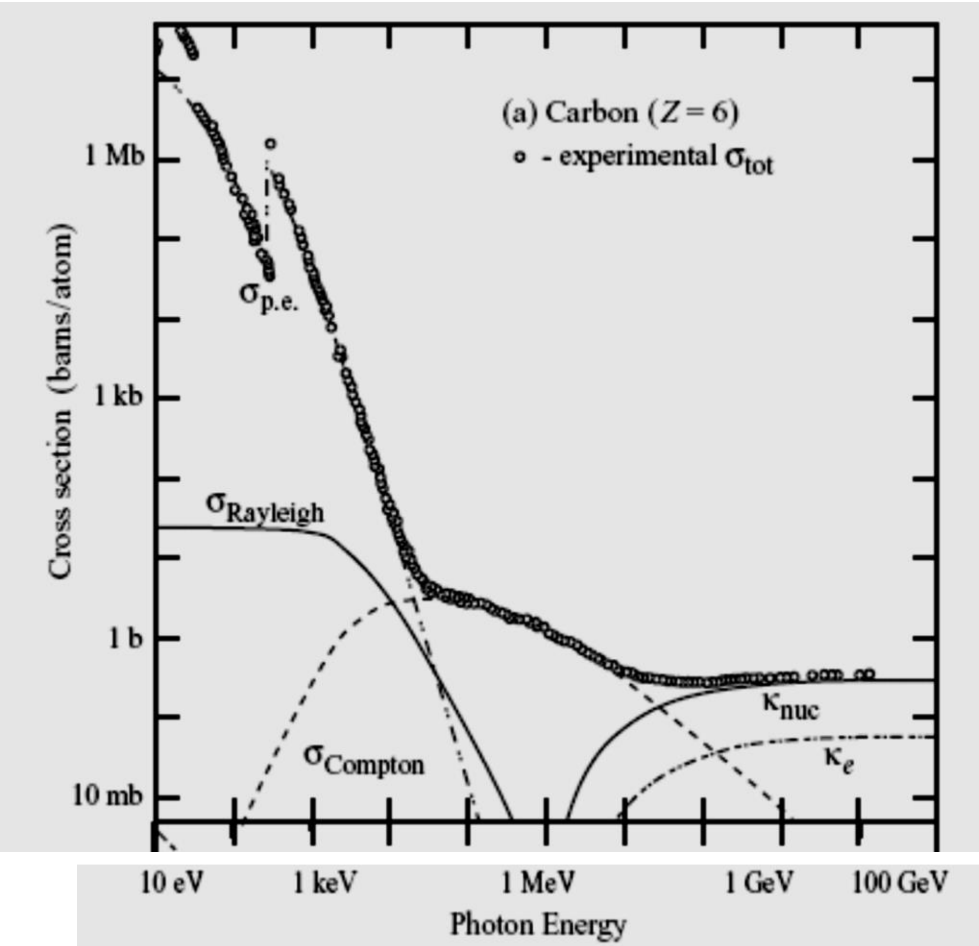
As the two diagrams are more or less identical, we would expect the cross sections to be similar.



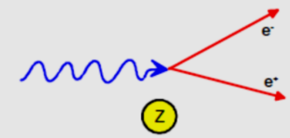
$$\sigma_{pair} = \frac{7}{9}\sigma_B \approx 0.45 mb \times Z^2$$

For $E_\gamma >> m_e c^2 = 0.5 MeV$: $\lambda = 9/7 X_0$

Average distance a high energy photon has to travel before it converts into an $e^+ e^-$ pair is equal to 9/7 of the distance that a high energy electron has to travel before reducing it's energy from E_0 to $E_0 * e^{-1}$ by photon radiation.



◆ Pair production



$$\gamma + nucleus \rightarrow e^+ e^- + nucleus$$

Only possible in the Coulomb field of a nucleus (or an electron) if $E_\gamma \geq 2 m_e c^2$

Cross-section (high energy approximation)

$$\sigma_{pair} \approx 4 \alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} \right)$$

independent of energy !

$$\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

$$\approx \frac{A}{N_A} \frac{1}{\lambda_{pair}}$$

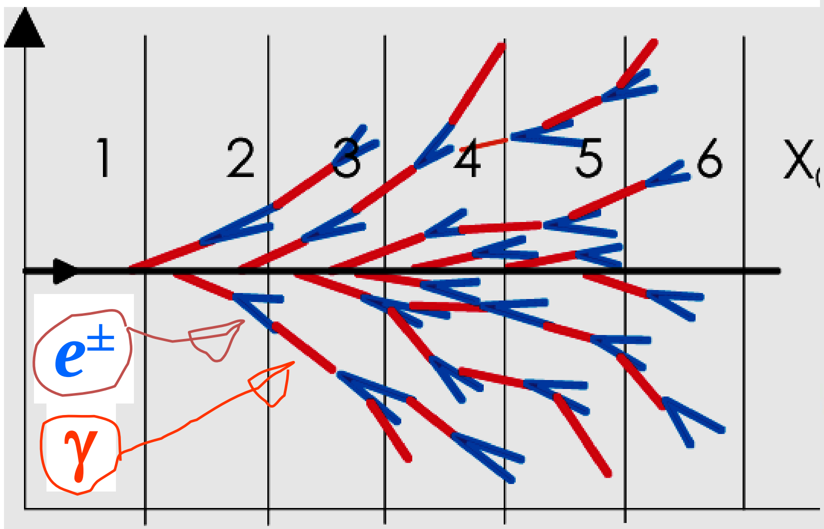
$$\lambda_{pair} = \frac{9}{7} X_0$$

Electromagnetic Calorimeter

Rossi B. Approximation to Shower Development.

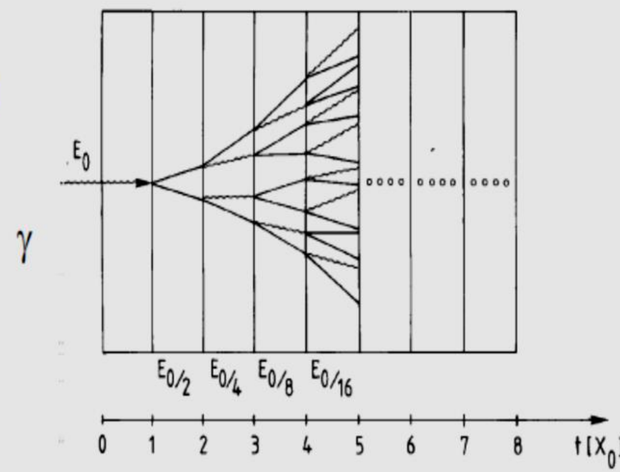
1) Electrons loses a constant amount of energy (ε) for each radiation length, X_0

2) Radiation and Pair production at all energies are described by the asymptotic formulae.



◆ Simple qualitative model

Consider only Bremsstrahlung and pair production. Symmetric energy splitting in each step.



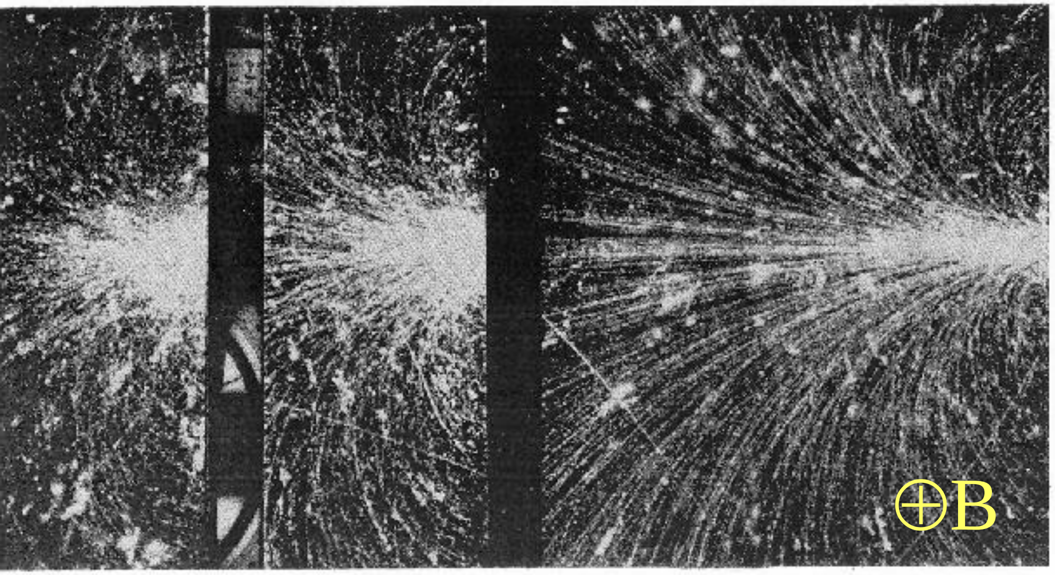
$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t)<E_c$

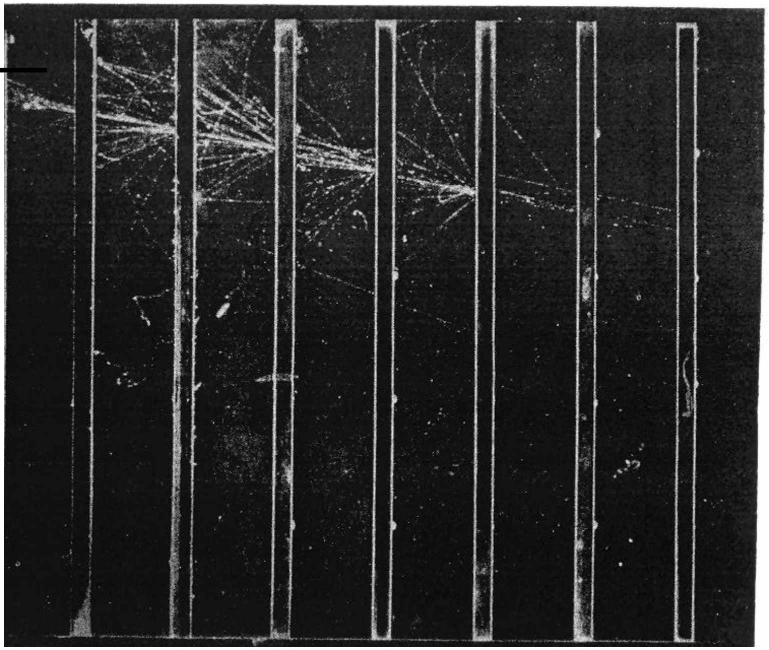
$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \qquad N^{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect → absorption.

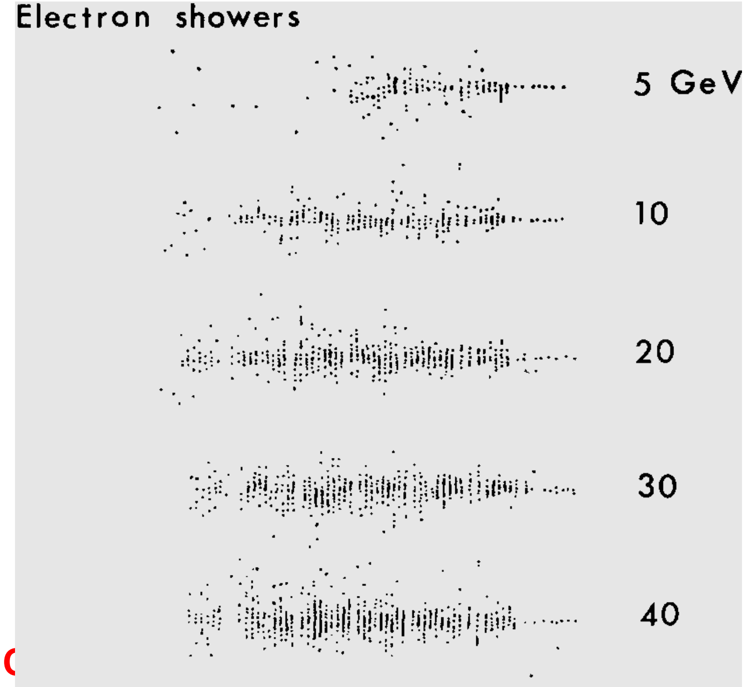
How a shower looks like

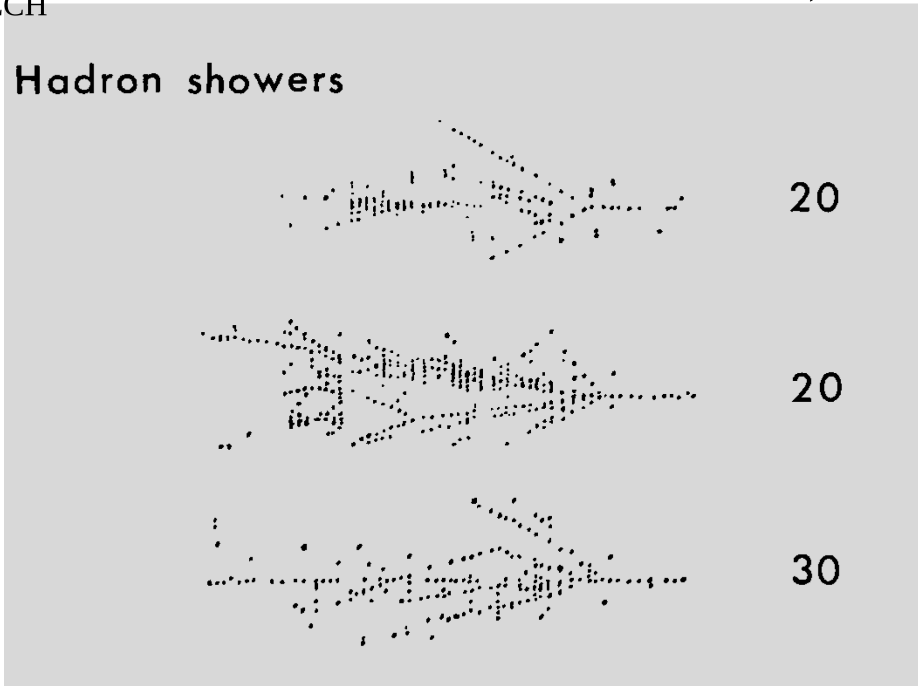


Electron shower in lead. 7500 gauss in cloud chamber. CALTECH

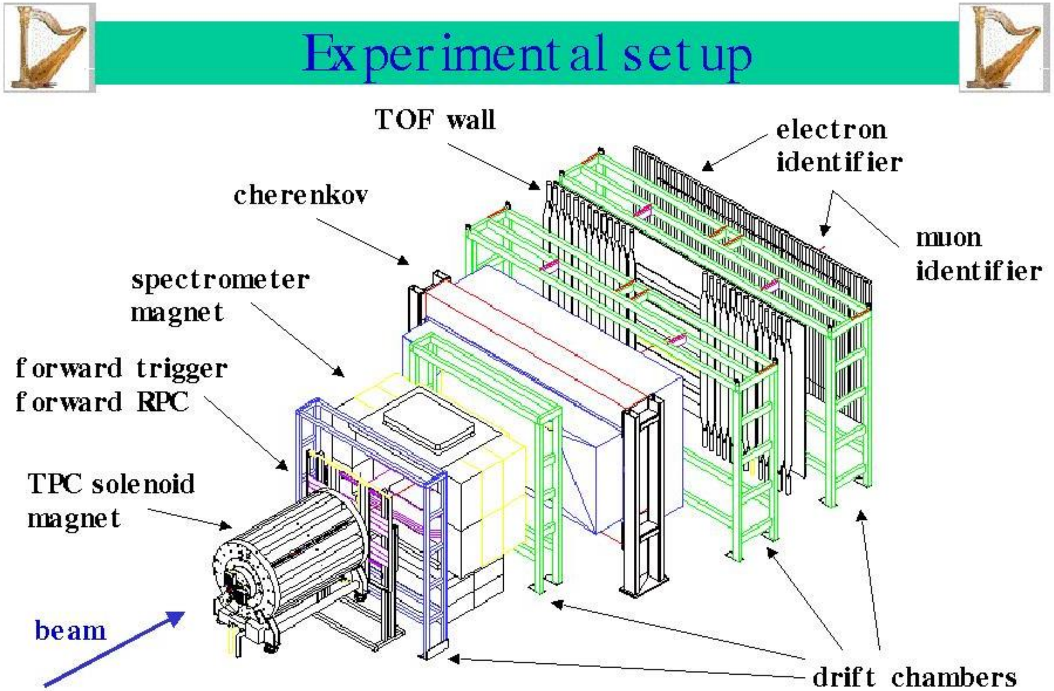


Electron shower in lead. Cloud chamber. W.B. Fretter, UCLA

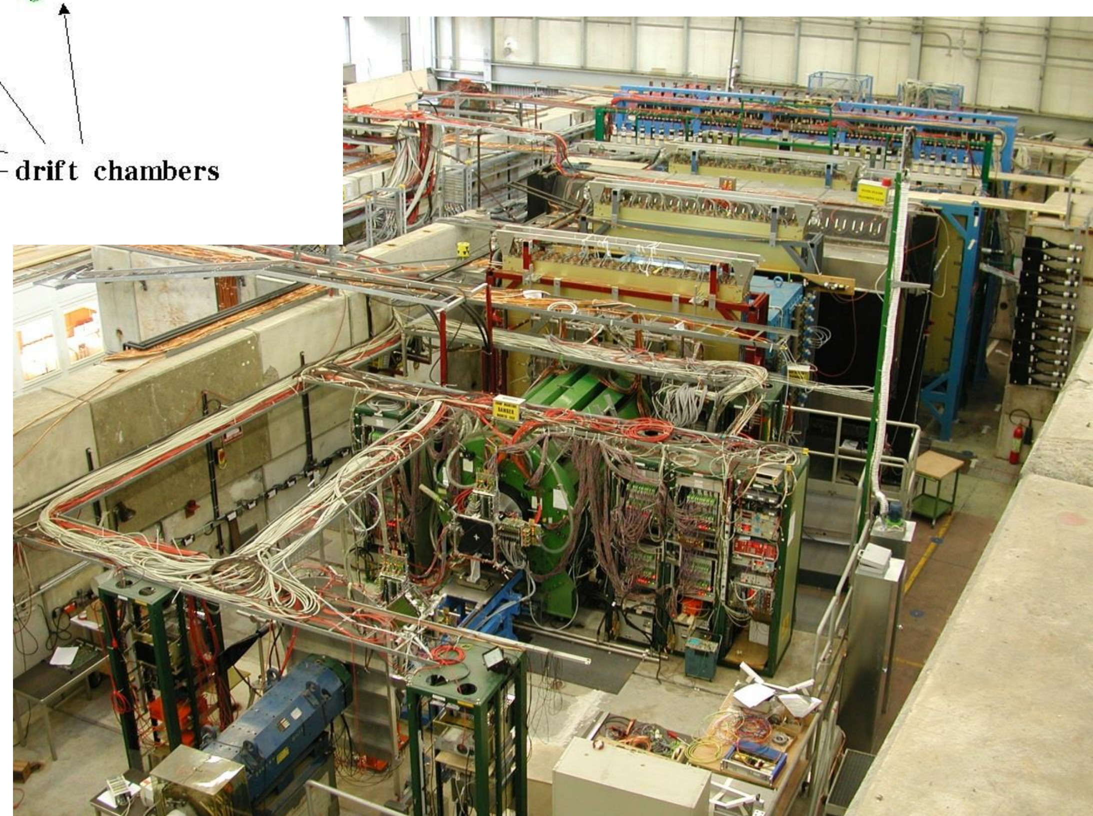




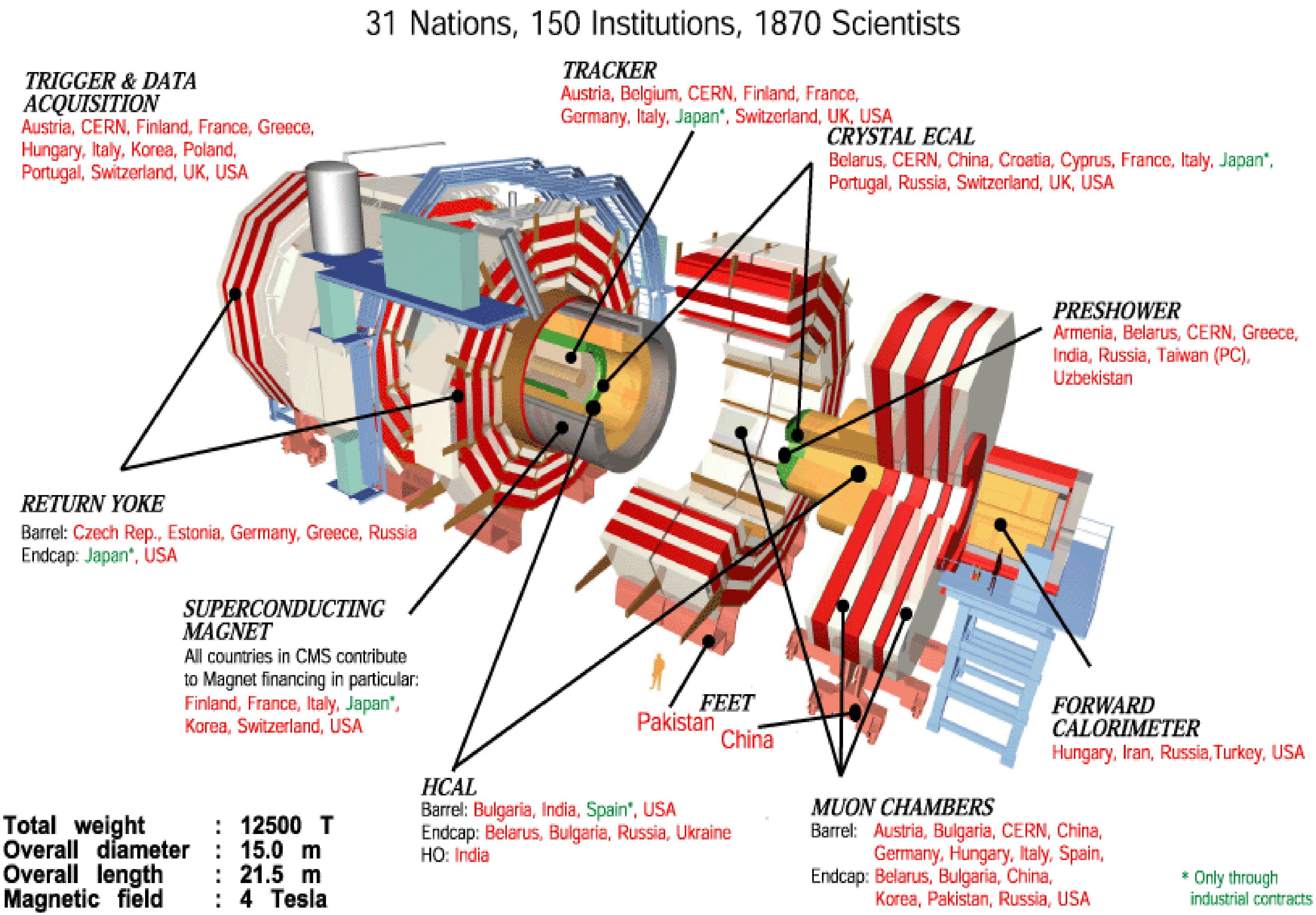
F.E. Taylor et al., IEEE NS 27(1980)30



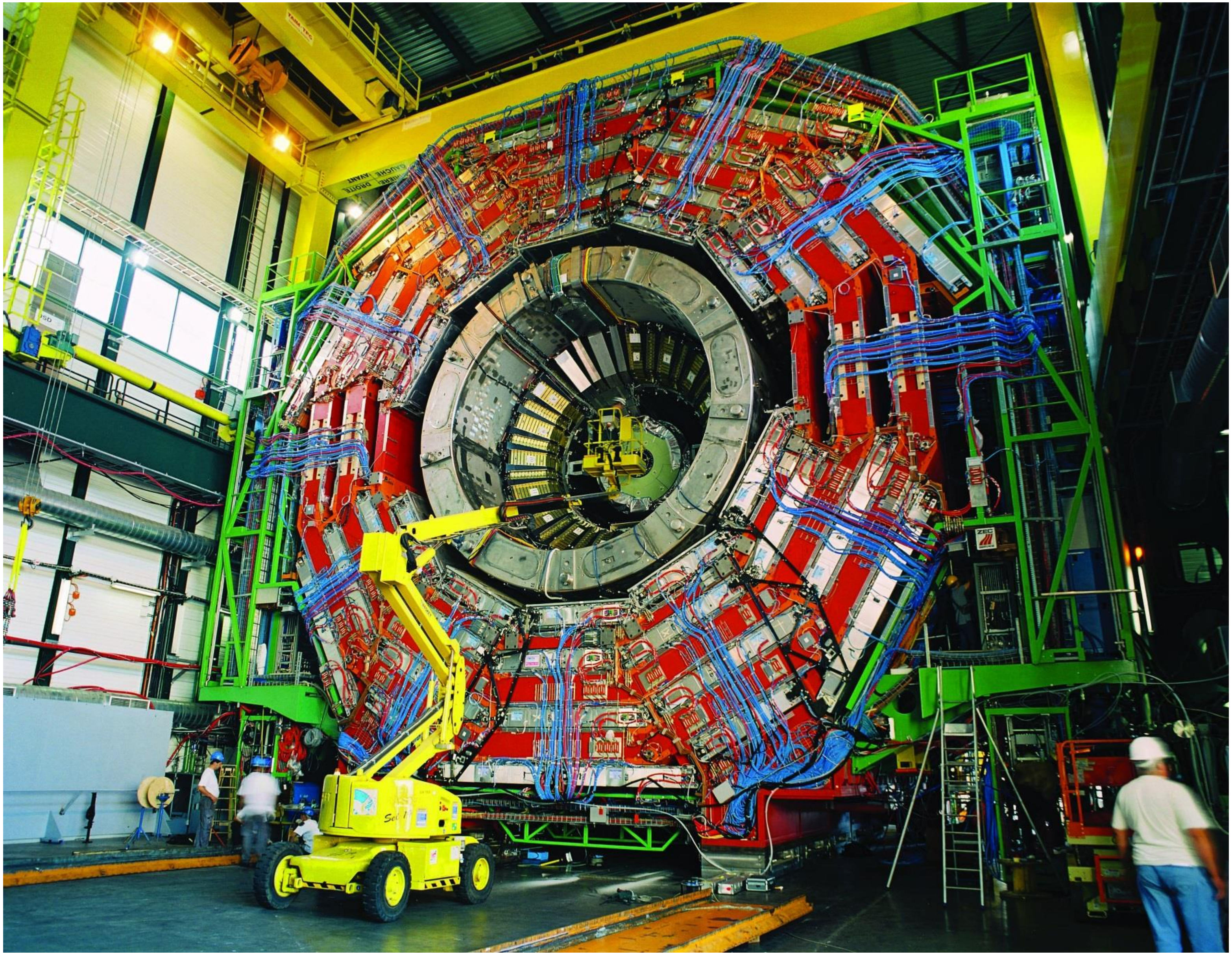
HAdrop**R**oduction experiment at CERN **P**S
(HARP)

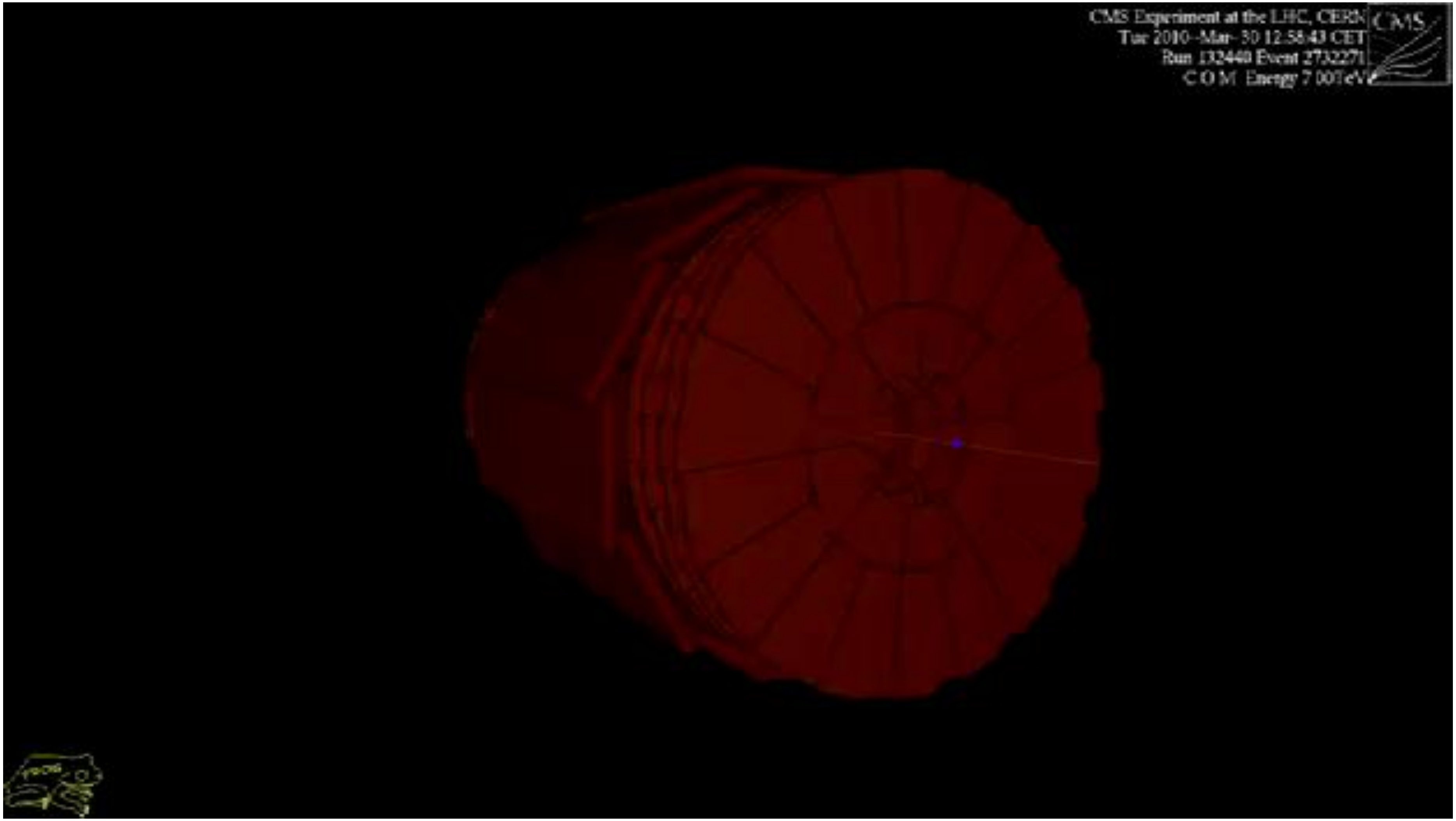


CMS Detector



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




CMS Experiment at the LHC, CERN
Tue 2010-Mar-30 12:58:43 CET
Run 132440 Event 2732271
C.O.M. Energy 7.00TeV
CMS

Изпит: 19.02 2015 г. 10:00, В29б

Край…

Конспект за изпита:

http://atomic.phys.uni-sofia.bg/Members/tsenov/subatomic-physics/conspect2014.pdf