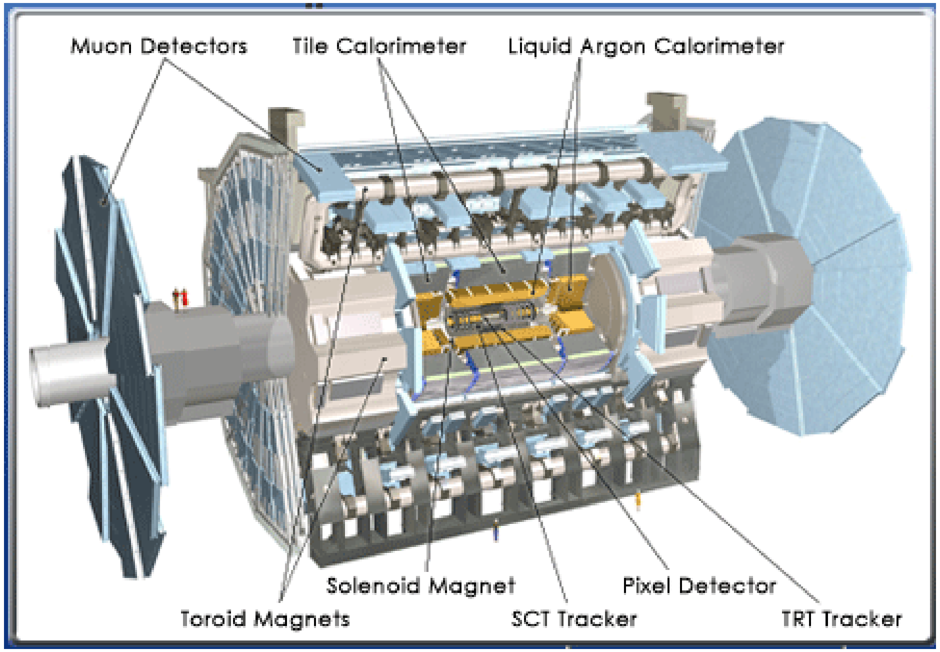
EP228 Particle Physics

Topic 7
Particle Detectors



Department of
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Course web page
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Oct 2012

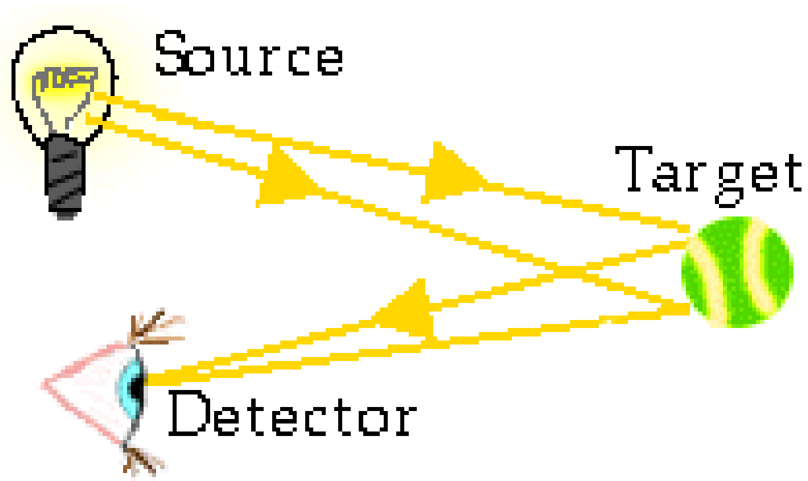
Outline

1. **Introduction**
2. **Bubble Chambers**
3. **Ionisation Detectors**
4. **Scintillators**
5. **Time of Flight Detectors**
6. **Cherenkov Detectors**
7. **Calorimeters**
8. **Big Detectors**
9. **Exercises**

- ***See also*:**
  - **http://www.cern.ch**
  - **http://en.wikipedia.org/wiki/Particle_Detectors**
  - **http://en.wikipedia.org/wiki/Large_Hadron_Collider**

1. Introduction

- A **particle detector** is a device used to detect, track, and/or identify high-energy particles
- Some detectors are also used to measure the energy and spin of a particle.



Detectors employed in HEP experiments record

position, *arrival time*, *momentum*, *energy* and *identity*

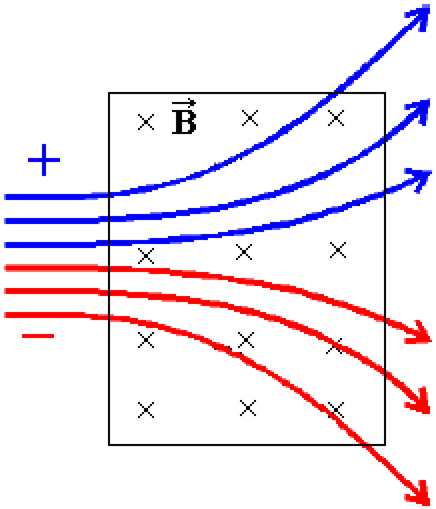
of particles.

Charged particles ($e^{\pm}$ p $K^{\pm}$ $\mu^{\pm}$ $\pi^{\pm}$)

can be detected through their ionisation in tracking chambers

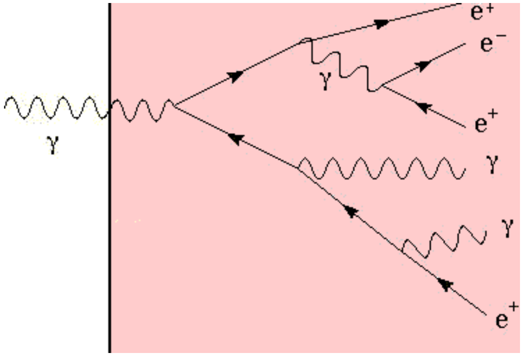
* a measure of the curvature of the track in a magnetic field gives a measure of its momentum

* a measure of the rate of ionisation loss (dE/dx) can be used to determine its type



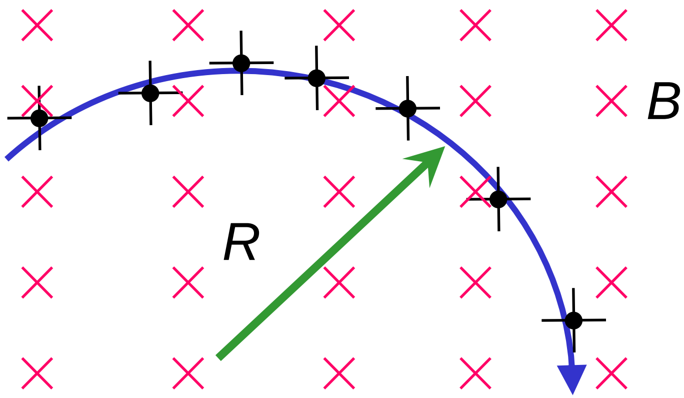
Neutral particles (γ n)

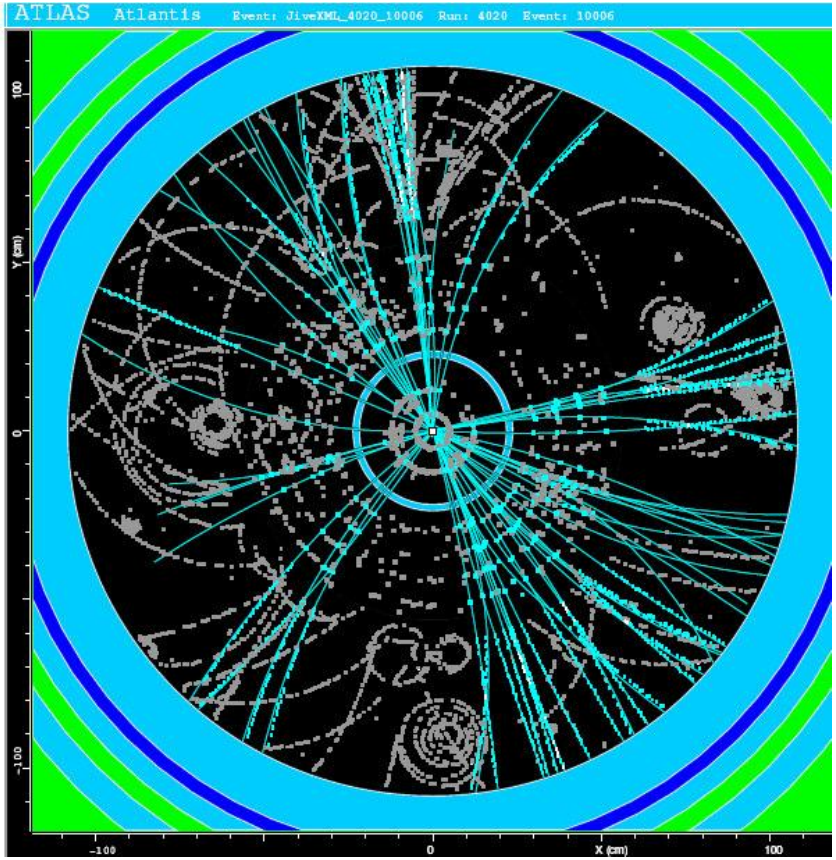
are detected via calorimeters, where their position and energy are measured.



We need charged particle tracking in HEP experiments to determine

- # of charged particles produced in a reaction
- the identity of a charged particle
- the momentum of a charged particle





$$\frac{mv^2}{R} = qvB \longrightarrow \boxed{p = mv = BqR} \longrightarrow \boxed{p(\mathrm{GeV}) = 0.3BR}$$

B in Tesla and R in meter

2. Bubble Chambers

- A bubble chamber consists of a vessel filled with a liquid (hydrogen or a mixture of neon and hydrogen at a temperature of about 30K) heated nearly to the boiling point.

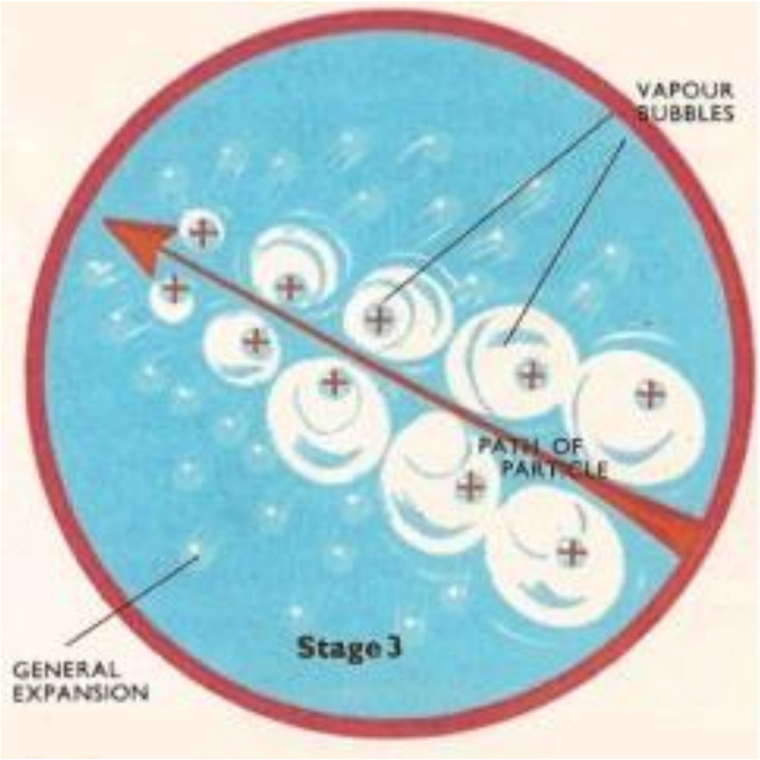
- When the pressure on the fluid is suddenly dropped, the fluid becomes overheated. At this moment electrically charged particles are fired through the chamber.

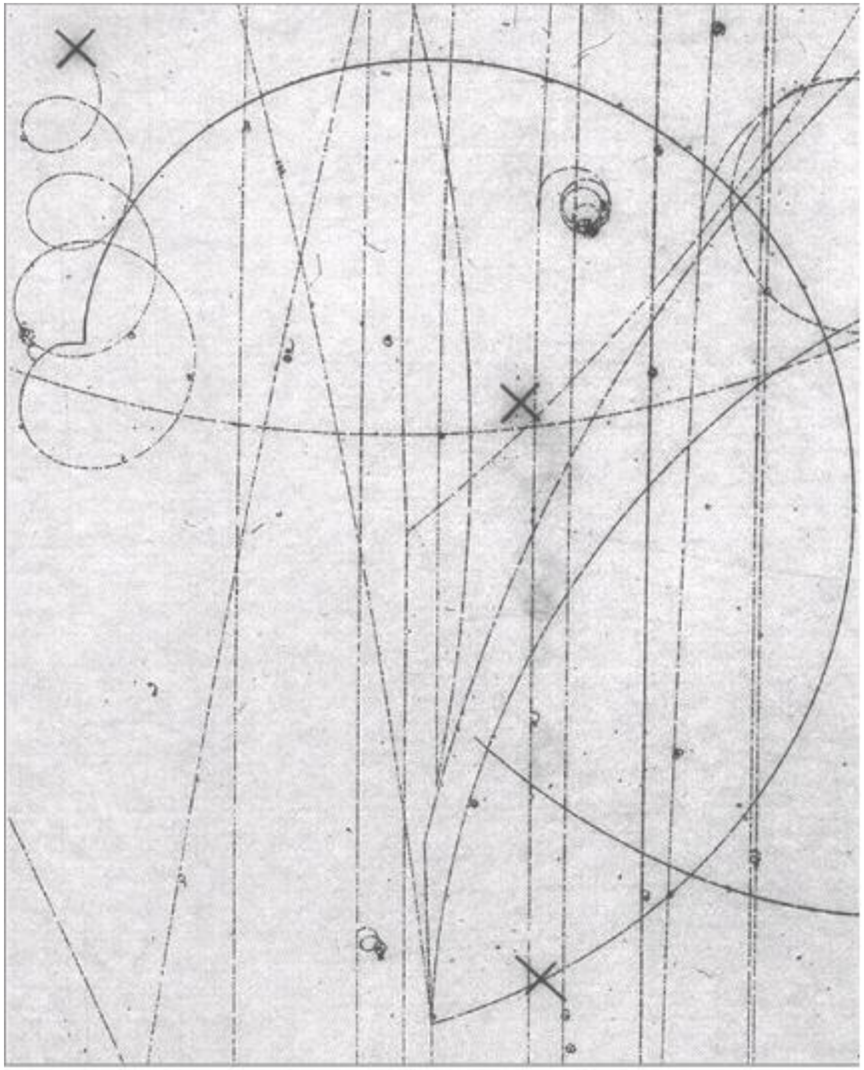
- The charged particles collide with liquid molecules, and give up some of their energy to them. The particles may knock electrons away from the molecules, leaving them electrically charged. In the heated, charged atoms and molecules surrounding the particles' paths, the liquid boils and forms a series of minute bubbles of vapor.

- Therefore, the fluid begins to boil along the paths of the particles, developing tiny bubbles that can be photographed.

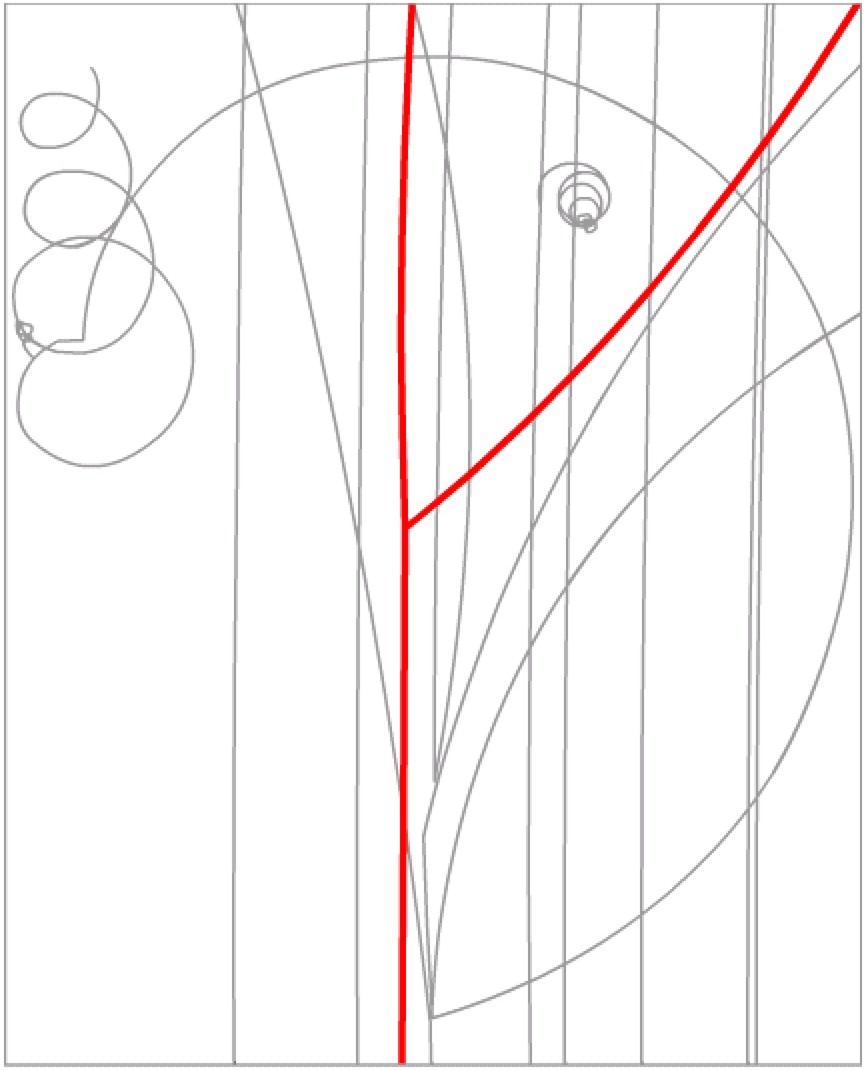
- The bubble chamber, invented by Donald Glaser in 1952.

- K - p collisions

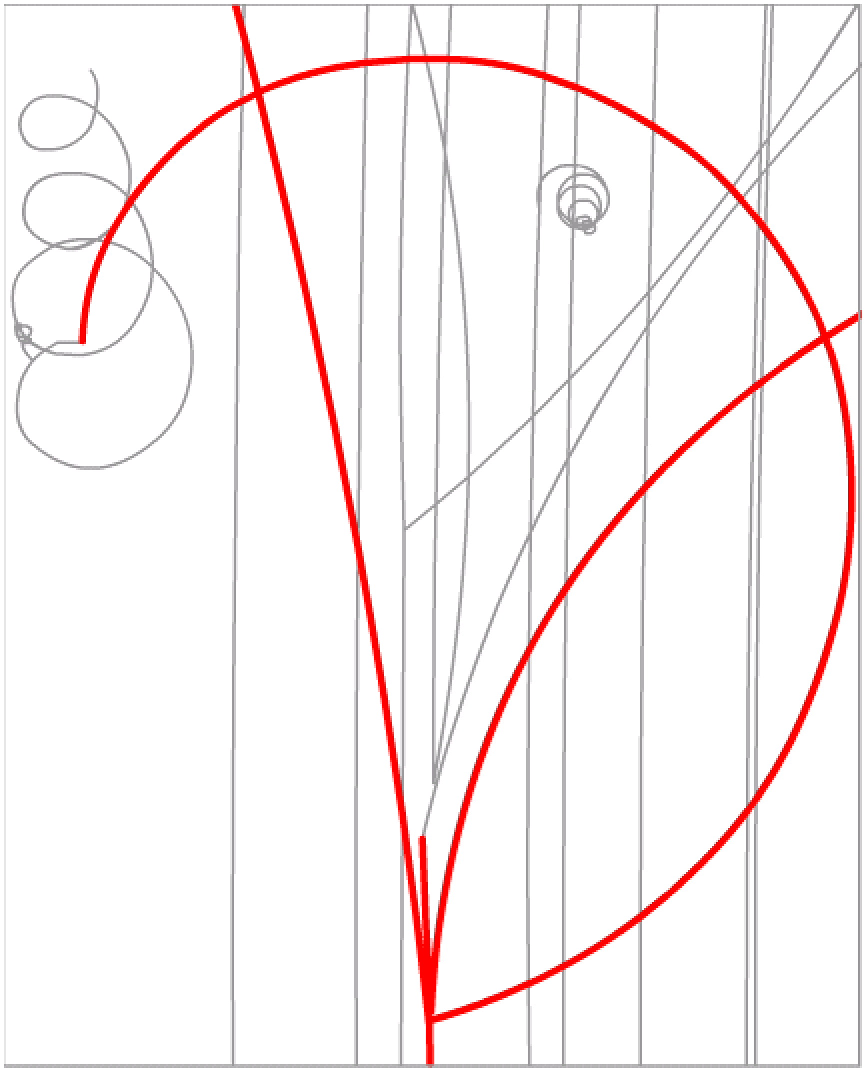




- K - p collisions



- K - p collisions



V0 Decays

The component of the momentum perpendicular to the original path of the neutral particle, $p_\perp$ is given by:

$$p_\perp = p \sin\theta \implies \sin\theta = \frac{p_\perp}{p}$$

But from similar triangles:

$$\sin\theta = \frac{\left(\frac{L}{2}\right)}{R} = \frac{L}{2R} \implies L = \frac{2R}{p} p_\perp$$

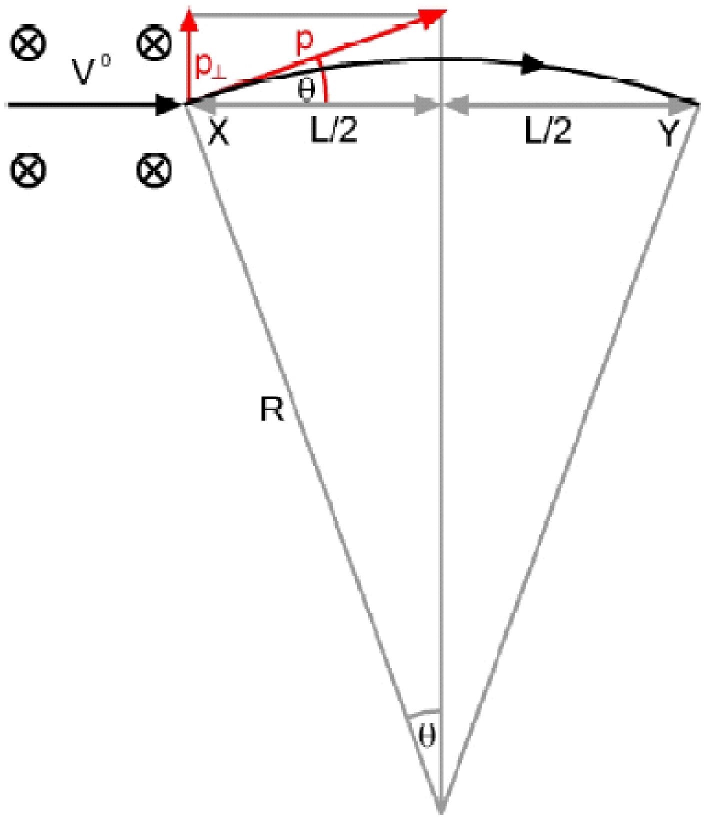
But the radius of curvature R is determined only by the momentum of the particle and the strength of the magnetic field:

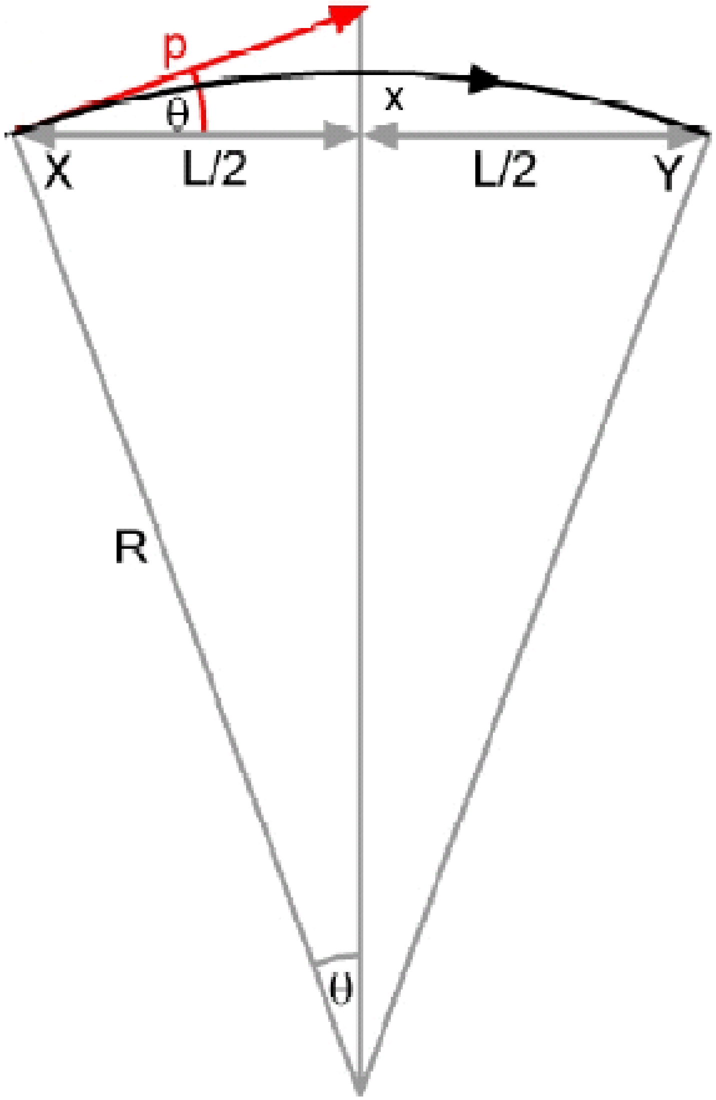
$$Bqv = \frac{mv^2}{R} \implies p = (Bq)R$$

so

$$L = \frac{2R}{BqR} p_\perp = \left(\frac{2}{Bq}\right) p_\perp$$

as required.



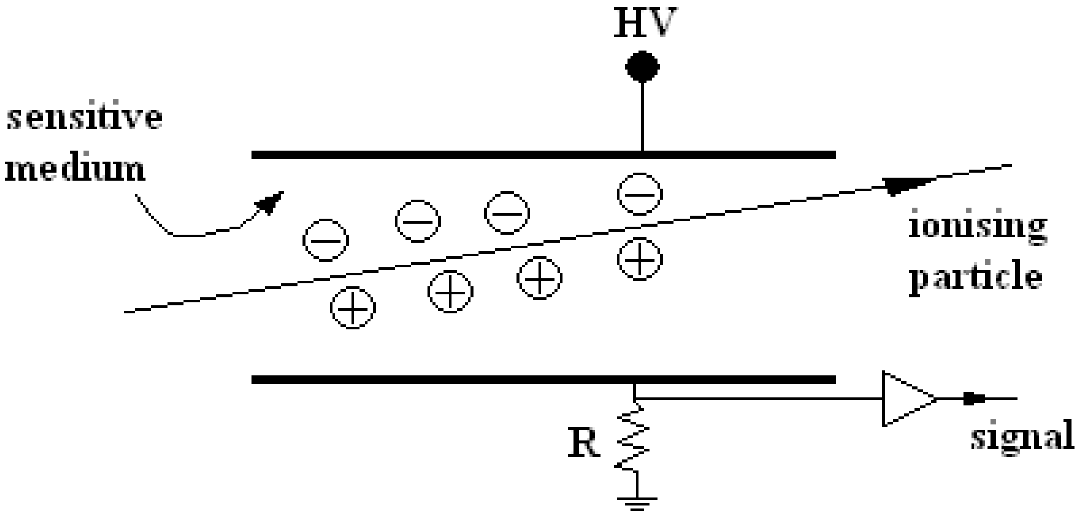


Question:
How can we determine the momentum p if we know only x, L and magnetic field B?

3. Ionisation Detectors

- Ionisation detectors are devices designed to measure the ionisation produced when an incident particle traverses some medium.
- When a charged particle traverses a medium of a detector, it ionises the medium and produces electron-ion pairs.

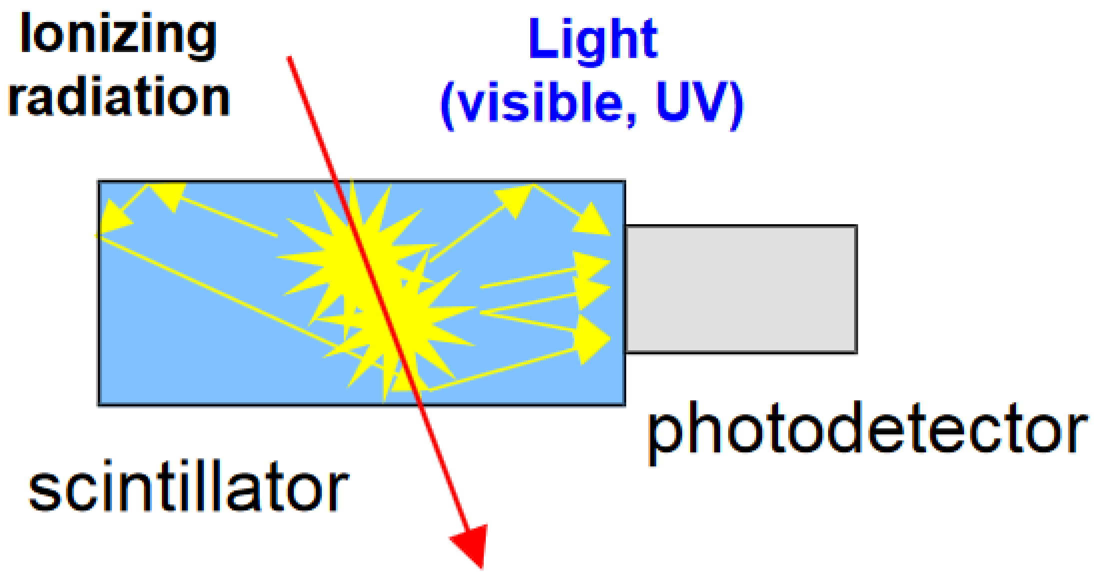
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$



4. Scintillation Detectors

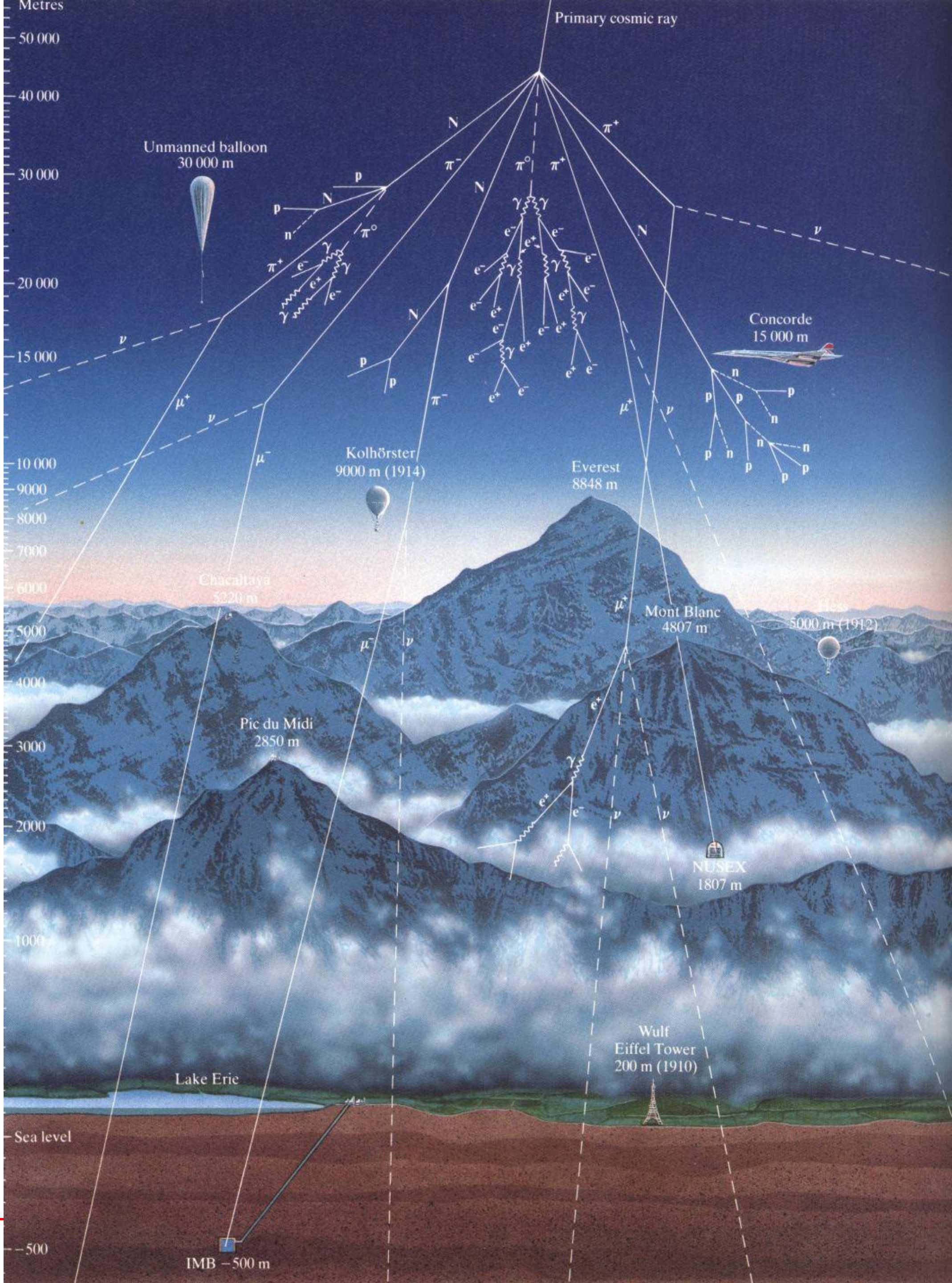
- A scintillator is a material that exhibits scintillation when excited by ionizing radiation.
- Scintillation is a flash of light produced in a transparent material by the passage of a particle (an electron, an alpha particle, an ion, or a high-energy photon).

Principle of the scintillation detectors.



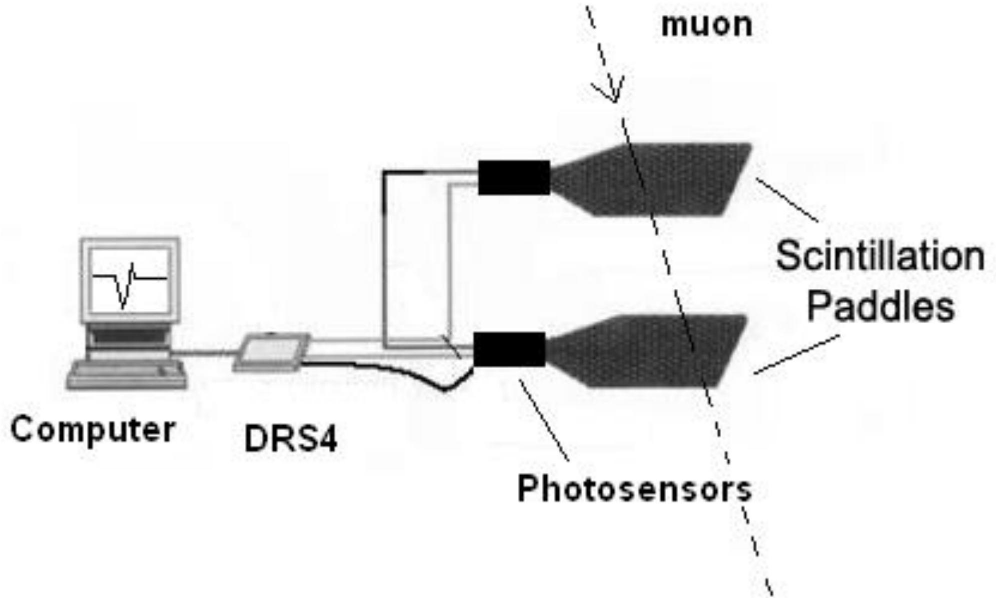
Cosmic Rays

Cosmic rays are energetic particles which do not originate from Earth.



Muon Telescope Project In Gaziantep University

- In this project, the fux and the angular distribution of the atmospheric muon particles have been measured in Gaziantep city at 850 m altitude in Turkey. Measurements are performed by a Muon Telescope detector system containing two scintillators, two photo-sensor modules and a DRS4 chip. The muon fux is found to be $\Phi = 185 \pm 18$ m^{-2} s^{-1} and the angular distribution is shown to be consistent with the theoretical predictions.



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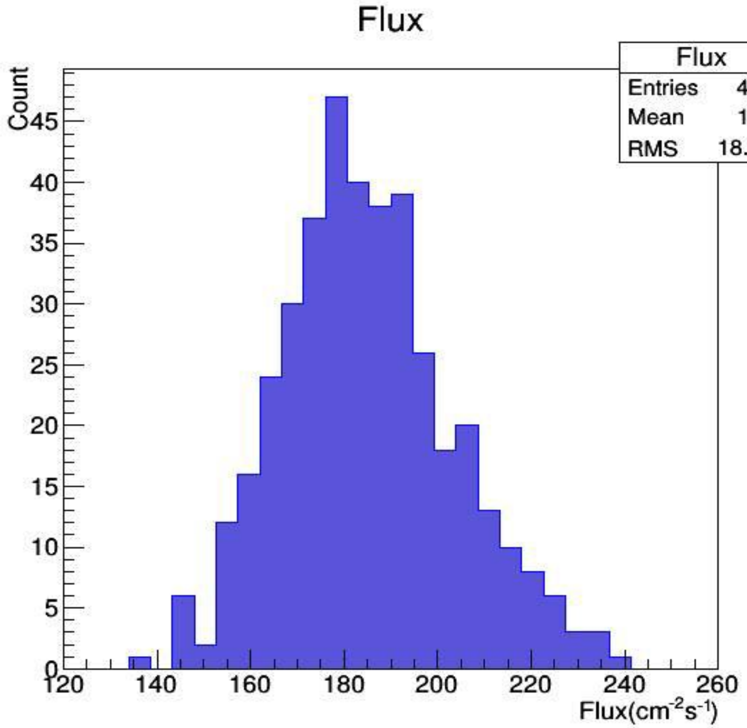
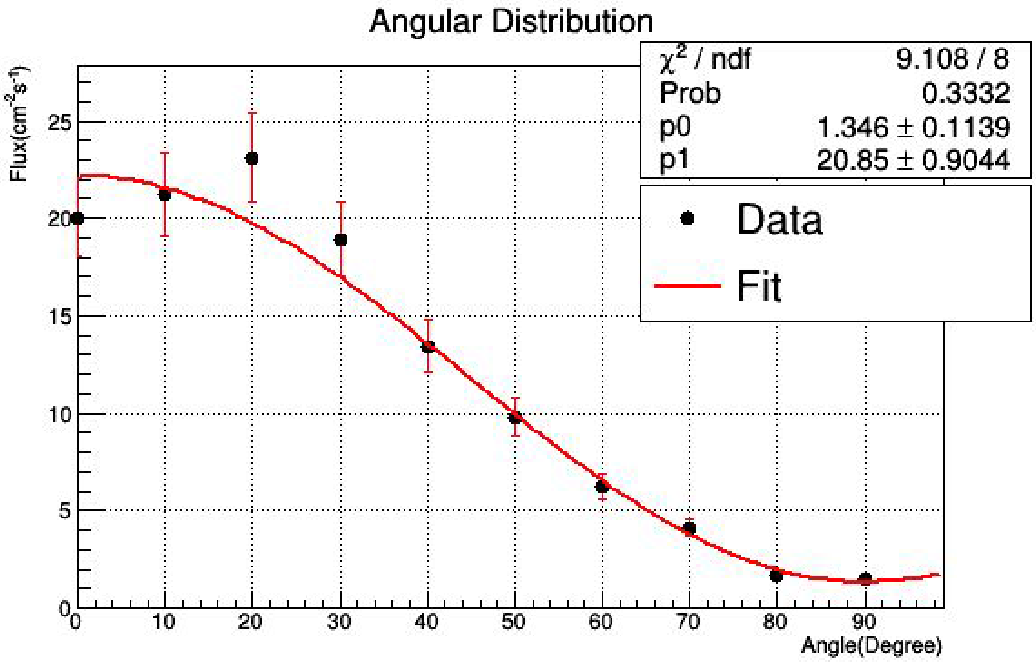
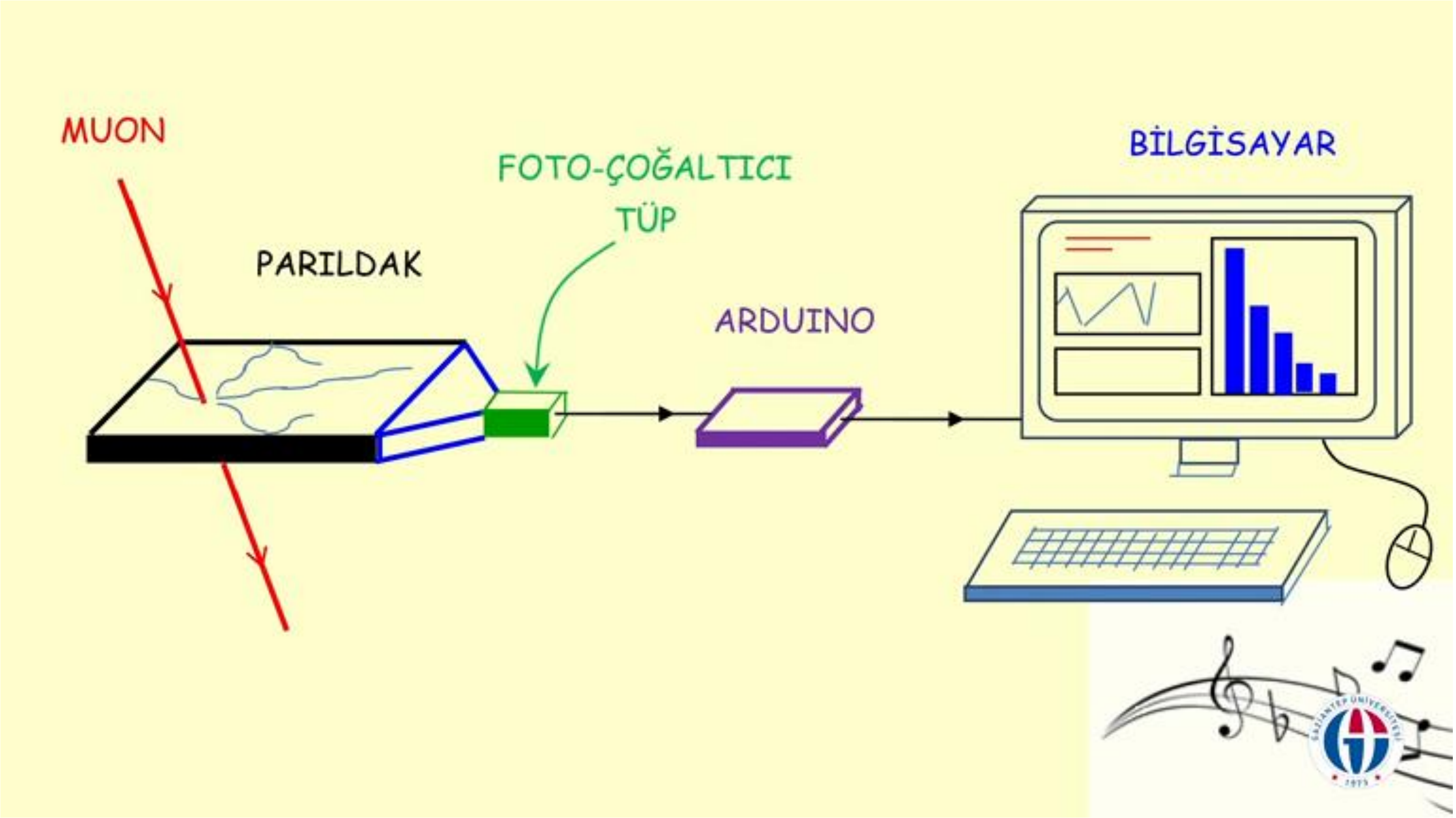




Sound of Cosmic Rays



https://www.youtube.com/watch?v=0u5h50xVkI8&t=0s

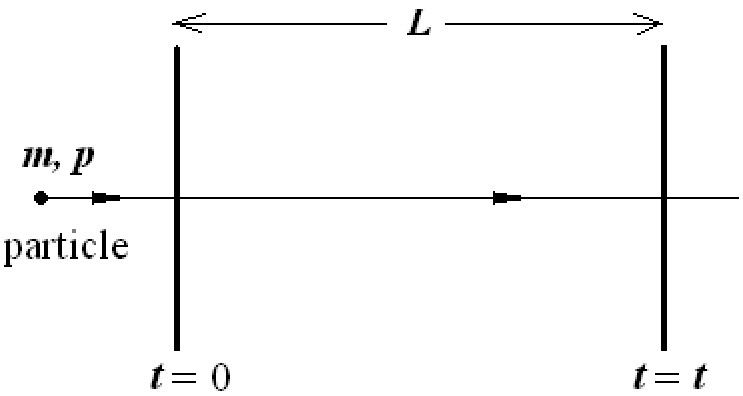
5. Time of Flight Detectors

- The time of flight (TOF) describes the method used to measure the time that it takes for a particle, object or stream to reach a detector while traveling over a known distance (*L*).

- This method is usually limited to low-energy partices with momenta less than about p = 4 Gev/c

- L: particles’path between two counters
- t: time to traverse L

$$\text{particle speed} = v = \frac{L}{t}$$



- For <u>two different particles</u> with the same momentum p time difference is

$$\Delta t = t_2 - t_1 = \frac{L}{v_2} - \frac{L}{v_1} = \frac{L}{c}\left(\frac{1}{\beta_2} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{c}\left(\frac{E_2}{pc} - \frac{E_1}{pc}\right) = \frac{L}{pc^2}([m_2^2c^4 + p^2c^2]^{1/2} - [m_1^2c^4 + p^2c^2]^{1/2})$$

- For known momentum and time, the mass and its resolution of a particle is given by:

measured mass:

$$m = p\sqrt{\frac{c^2t^2}{L^2} - 1}$$

mass resolution:

$$\frac{dm}{m} = \sqrt{\left(\frac{dp}{p}\right)^2 + \gamma^4\left(\frac{dt}{t}\right)^2}$$

Example 1: Calculate the minimum flight path neccessary to distinguish pions from kaons if they have momentum 3 GeV/c and TOF can be measured with an accuracy of 200 ps.

Solution

$$\Delta t = \frac{L}{pc^2}([m_2^2c^4 + p^2c^2]^{1/2} - [m_1^2c^4 + p^2c^2]^{1/2})$$

$$\Delta t = \frac{L}{c}([1 + m_2^2c^4 / p^2c^2]^{1/2} - [1 + m_1^2c^4 / p^2c^2]^{1/2})$$

$$200 \times 10^{-12} s = \frac{L}{3 \times 10^8 m/s}([1 + 0.494^2 / 3^2]^{1/2} - [1 + 0.140^2 / 3]^{1/2})$$

Solving for *L*:

$$L = 4.8m$$

Example 2: The momentum of a particle is measured as *p* = 2.0 ± 0.1 GeV/c. If the time to travel the distance *L* = 6.0 m in TOF detector, whose time resolution is *dt* = 10.0 ps, is measured as *t* = 20.05 ns, determine the mass of and the mass resolution for this particle.

Solution

$$m = p\sqrt{\frac{c^2t^2}{L^2} - 1} = 2\sqrt{\frac{(3\times10^8)^2(20.05\times10^{-9})^2}{5^2} - 1} = 0.1415\ \text{GeV/c}^2$$

$$dm = m\sqrt{\left(\frac{dp}{p}\right)^2 + \gamma^4\left(\frac{dt}{t}\right)^2}$$

$$= 0.1415\sqrt{\left(\frac{0.1}{2}\right)^2 + (14.2)^4\left(\frac{10.00\times10^{-12}}{20.05\times10^{-9}}\right)^2} = 0.0158\,\text{GeV/c}^2$$

Therefore: $m = 141.5 \pm 15.8\ \text{MeV/c}^2$ (charged pion)

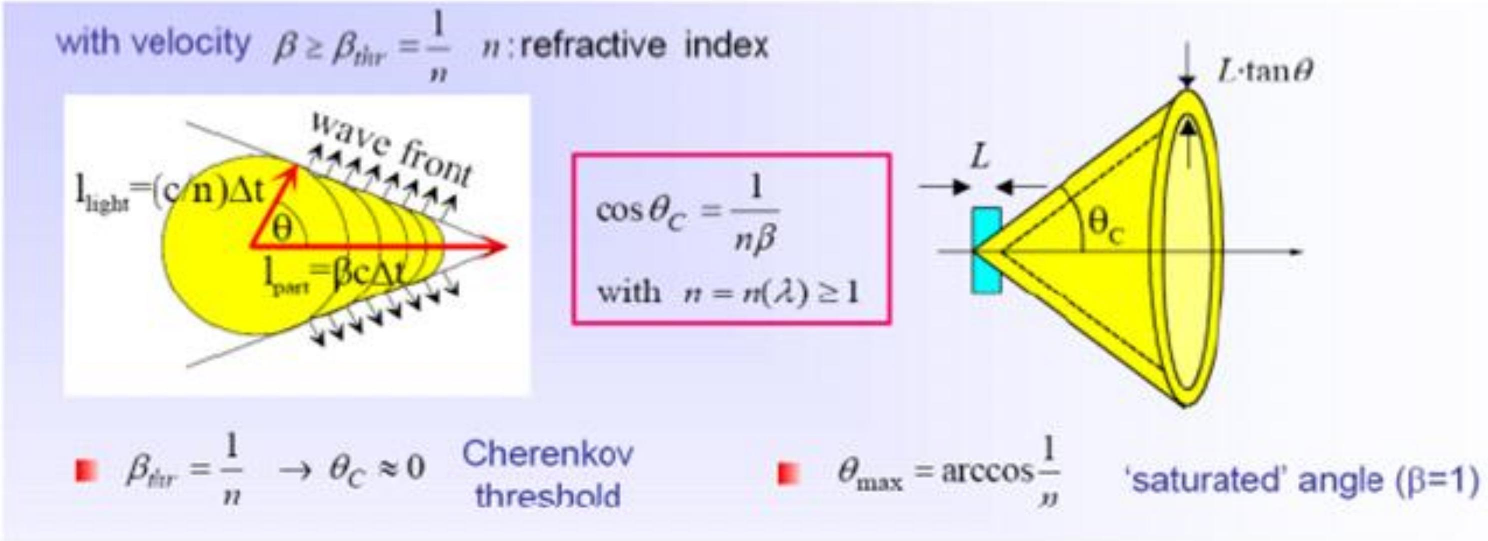
6. Cherenkov Detectors

- If the velocity of a charged particle is larger than the velocity of light in the medium v > c/n (n: refractive index), it emits 'Cherenkov Radiation' with cone angle

$$\cos\theta_c = \frac{1}{n\beta} \quad (\beta = v/c)$$

- Number of photons generated (*N*) per unit length (*dx*) can be found from for the wavelength (lambda)is given by:

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\hbar c\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \quad (\alpha = 1/137,\ \hbar = c = 1)$$



Example 3: Calculate number of generated photons/cm for the visible light (400-700 nm) in water (n=1.33) for charged particle of veloctiy beta ~ 1.

Solution

$$\frac{dN}{dx} = \int_{400nm}^{700nm} \frac{2\pi}{137}\left(1 - \frac{1}{1.33^2}\right)\frac{d\lambda}{\lambda^2} = 215\,\text{photons}/\,cm$$

Example 4: Compare Cherenkov angles of the pions and kaons of momentum p = 1 GeV/c in water (n=1.33).

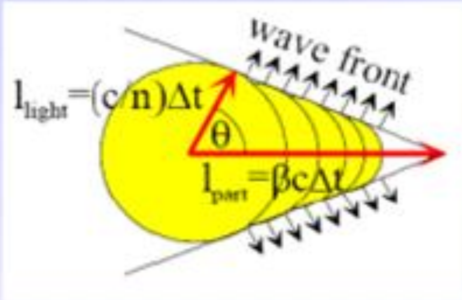
Solution

$$p^{kaon} = p^{pion} = 1\,\text{GeV/c} \quad \rightarrow \beta^{pion} = 0.99034 \;\; \text{and} \; \beta^{kaon} = 0.89657$$

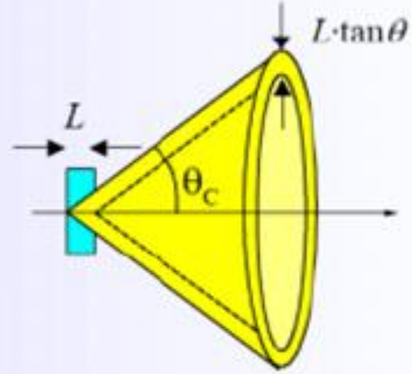
$$\cos\theta_c^{pion} = \frac{1}{(1.33)(0.99034)} = 0.7592 \quad \rightarrow \; \theta_c^{pion} = 40.6^o$$

$$\cos\theta_c^{kaon} = \frac{1}{(1.33)(0.89657)} = 0.8386 \quad \rightarrow \; \theta_c^{kaon} = 33.0^o$$

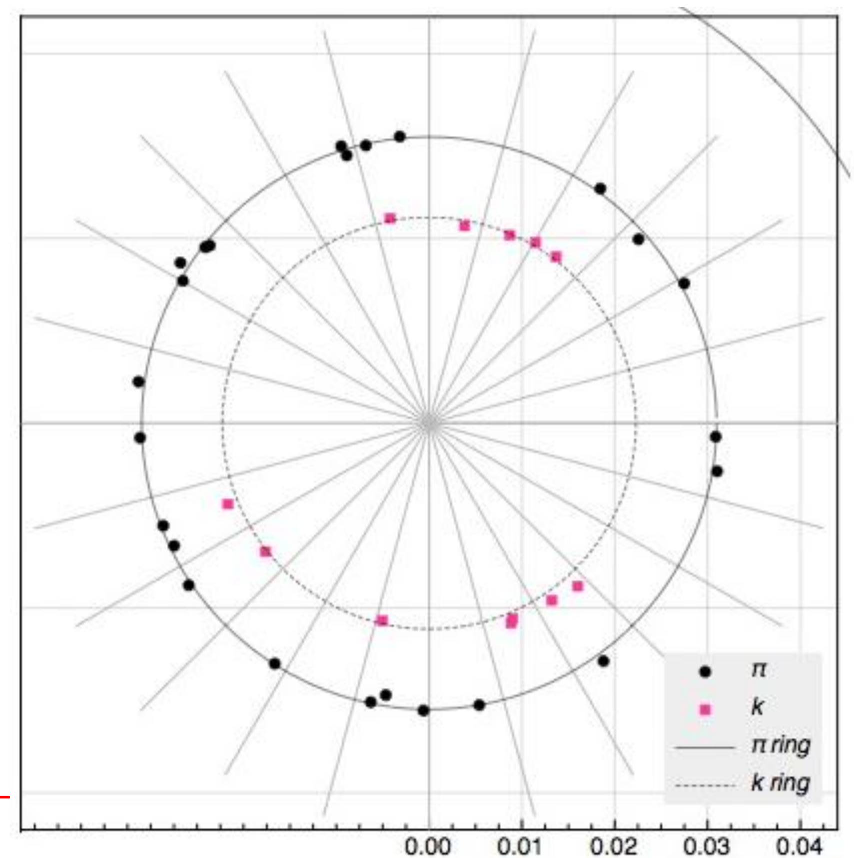
with velocity $\beta \geq \beta_{thr} = \frac{1}{n}$ n: refractive index

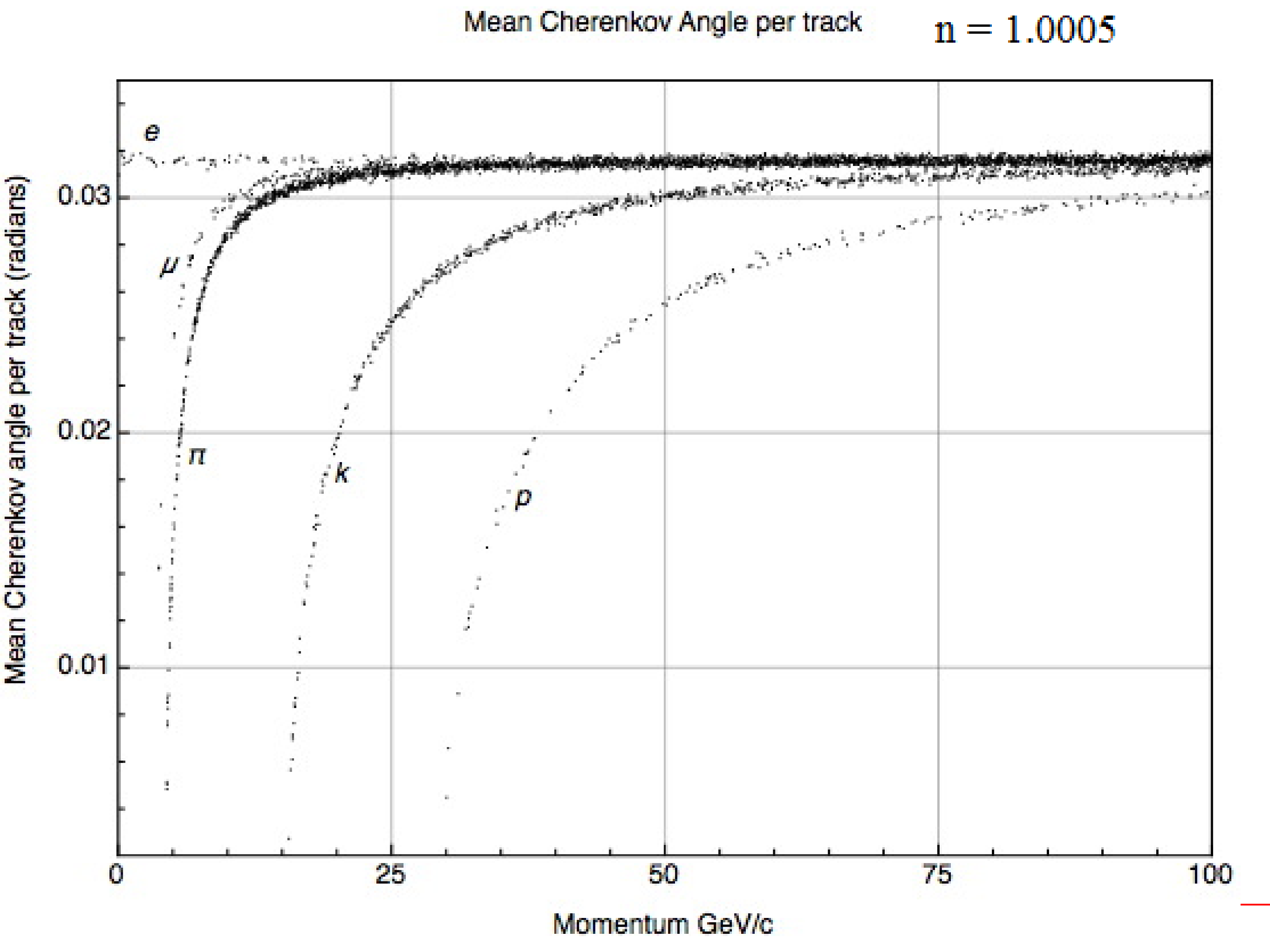


$$\cos\theta_C = \frac{1}{n\beta}$$
with $n = n(\lambda) \geq 1$



- $\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$ Cherenkov threshold
- $\theta_{max} = \arccos\frac{1}{n}$ 'saturated' angle (β=1)

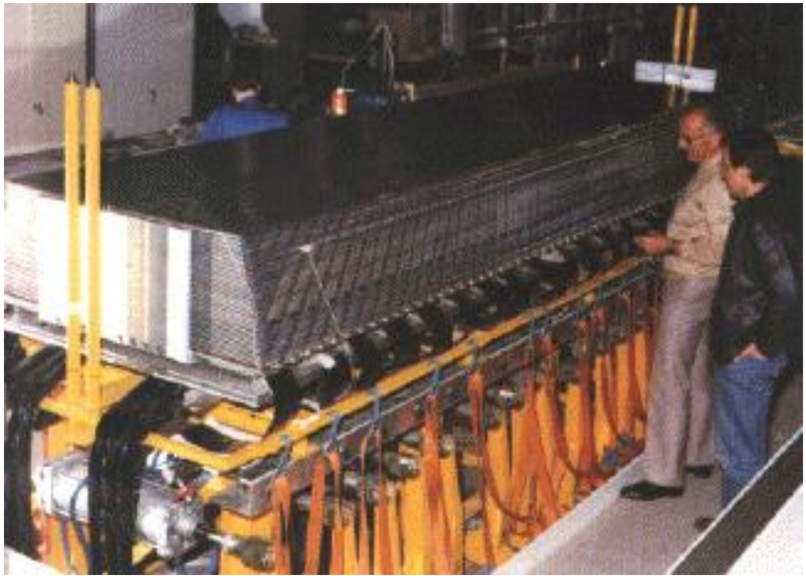




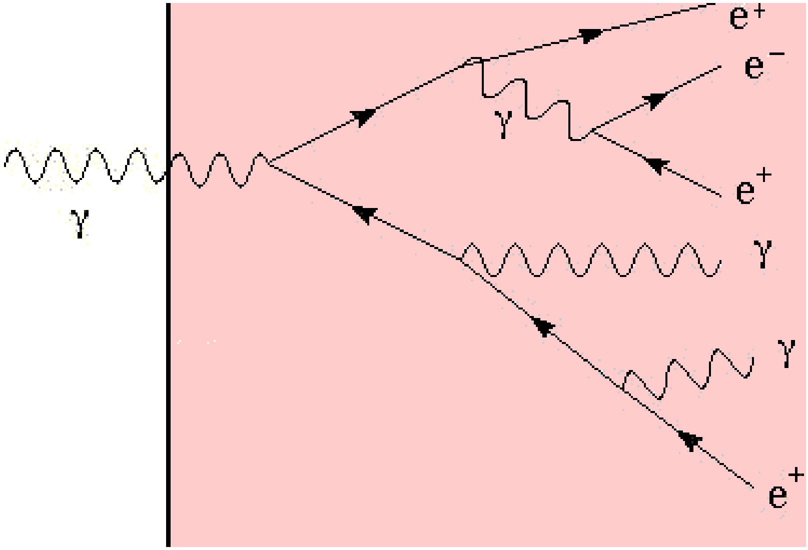
Mean Cherenkov Angle per track
n = 1.0005
Mean Cherenkov angle per track (radians)
0.03
0.02
0.01
0
25
50
75
100
Momentum GeV/c
e
μ
π
k
p

7. Calorimeters

For electrons and photons of high energy, a dramatic result of the combined phenomena of **bramsstrahlung** and **pair production** is the occurance of cascade showers.

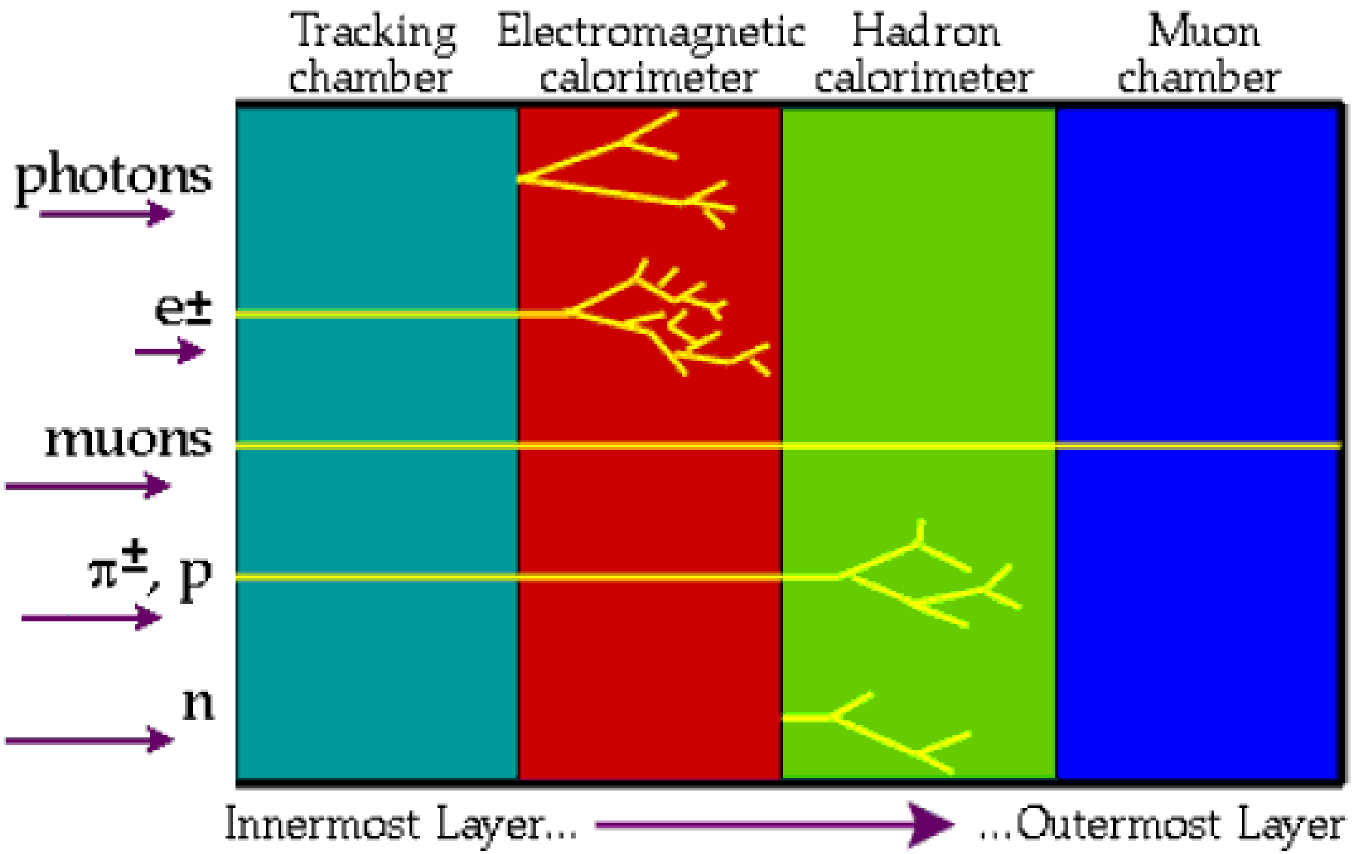


A parent electron will radiate photons, which converts to pairs, which radiate and produce fresh pairs in turn, the number of particles increasing exponentially with depth in the medium.

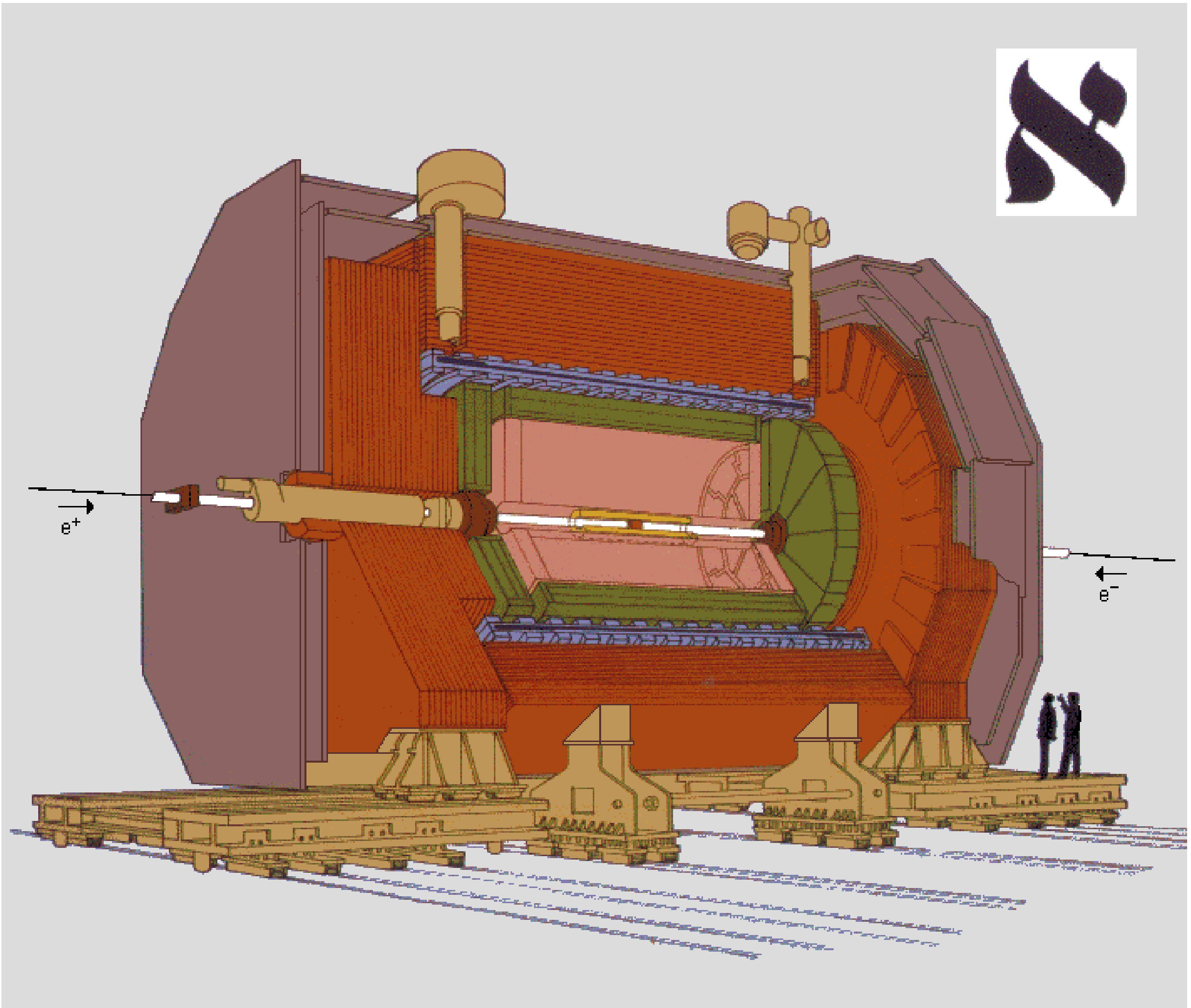


8. Big Detectors

- Different particle types interact differently with matter e.g. photons do not feel a magnetic field.
- *Therefore, we need different types of detectectors to measure different types of particles.*

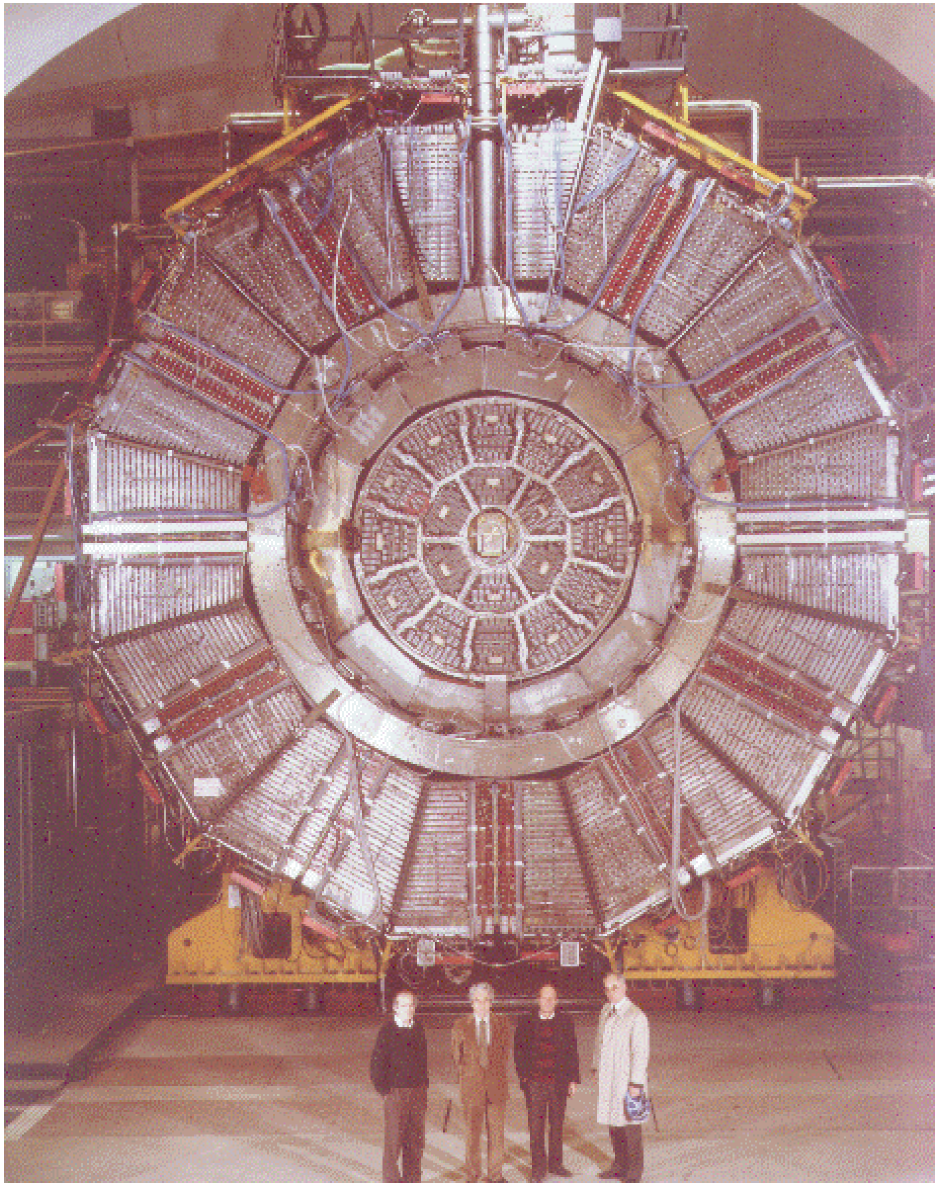


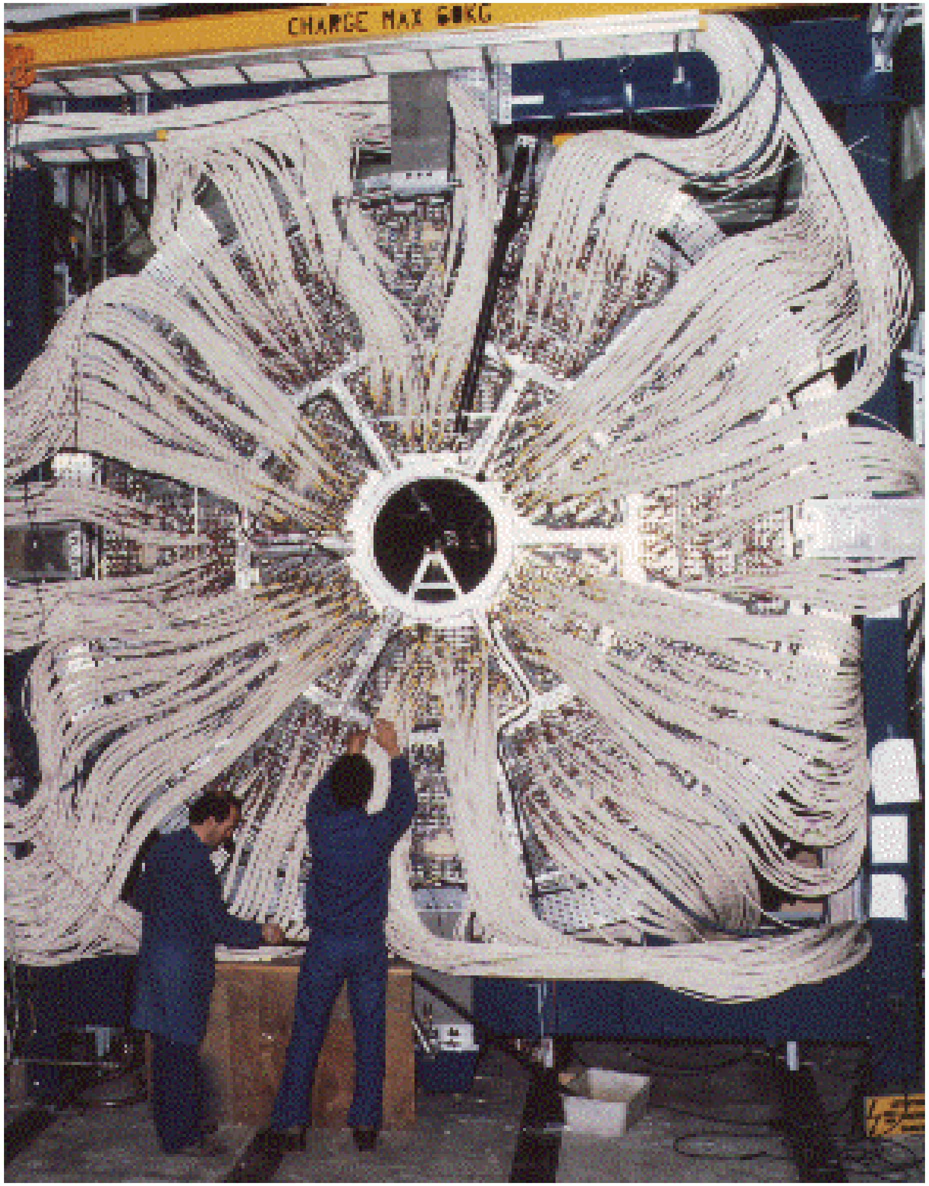
The ALEPH Detector used between 1989-2000 at LEP



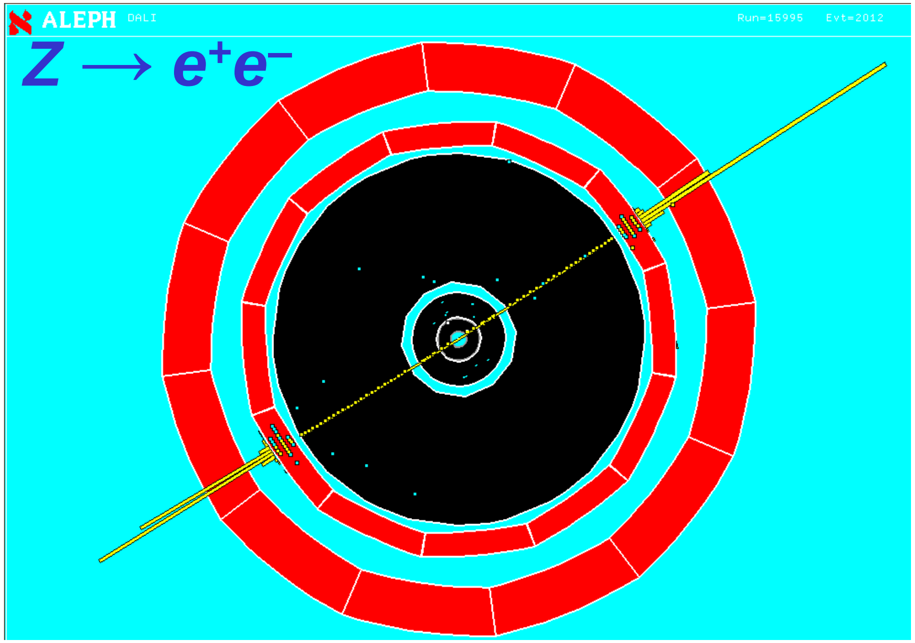
- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

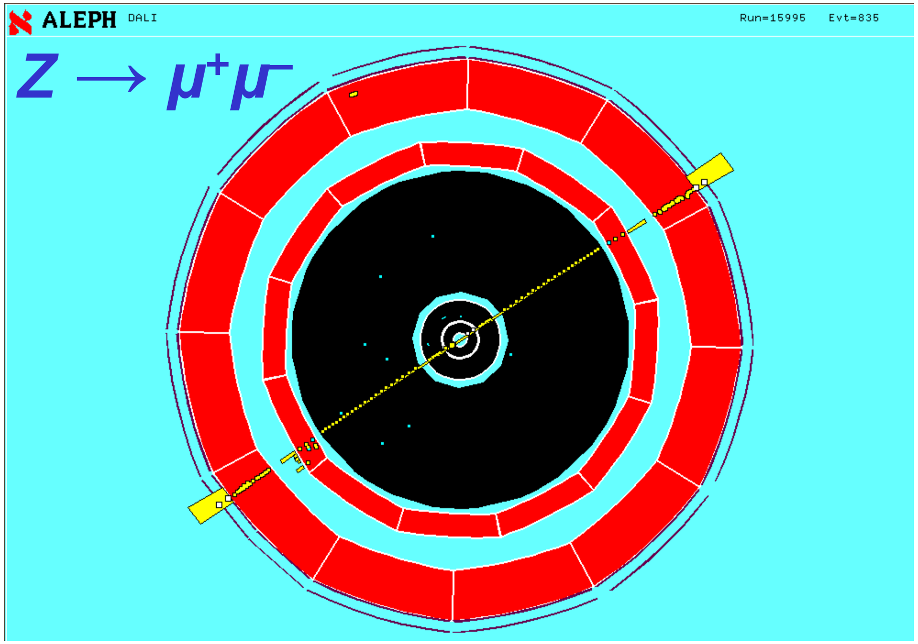
The ALEPH Detector

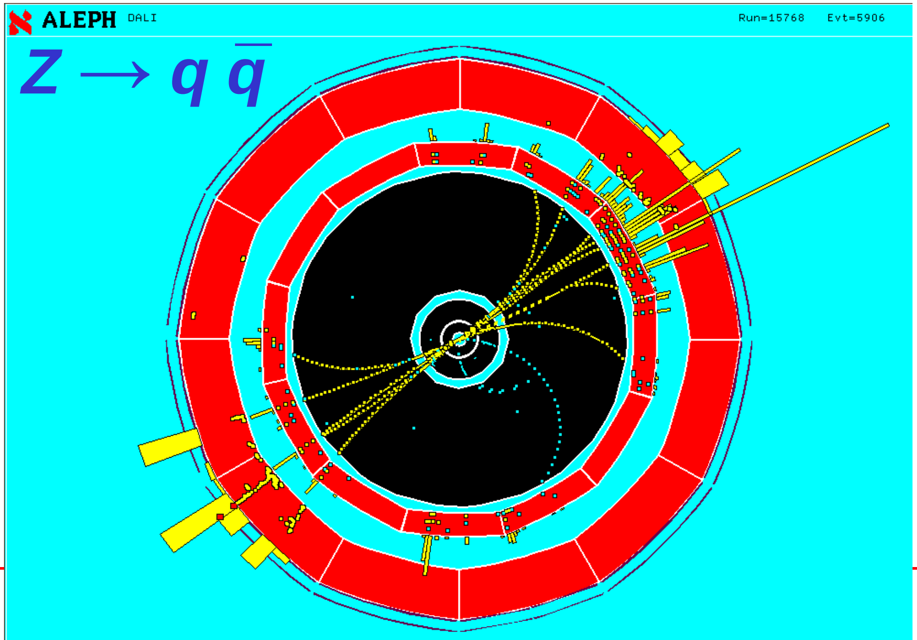




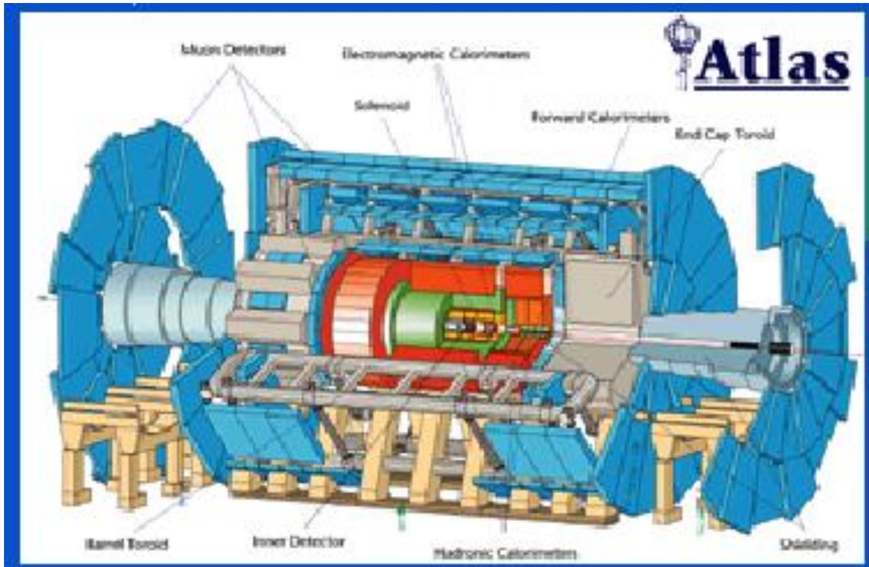
Recorded ALEPH Events

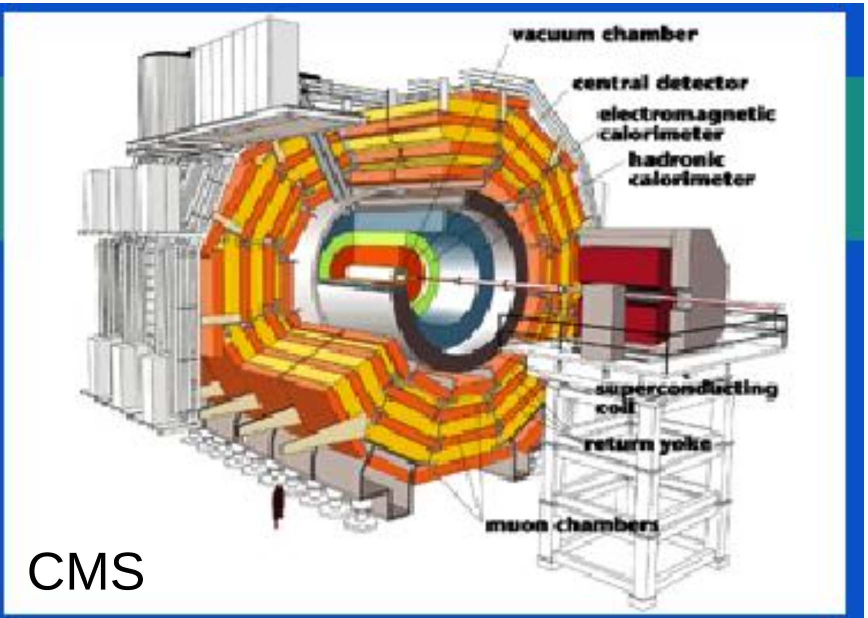


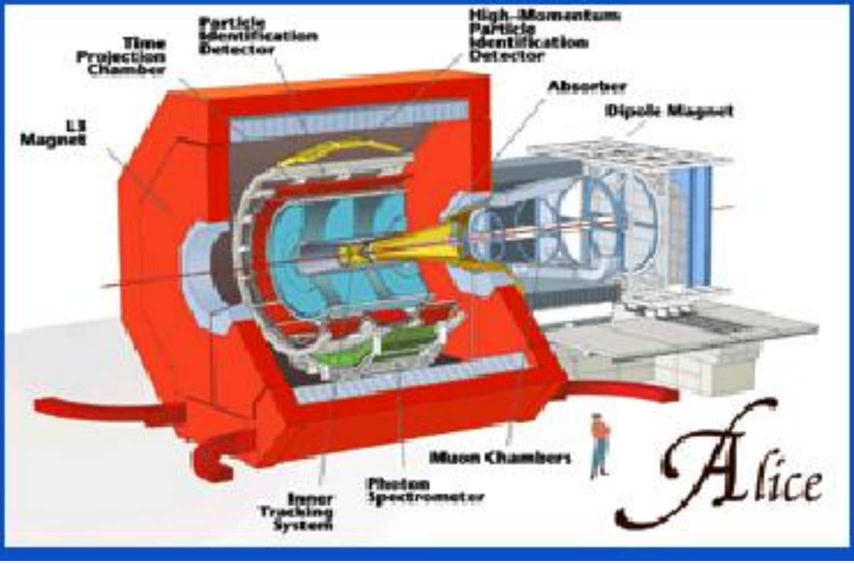


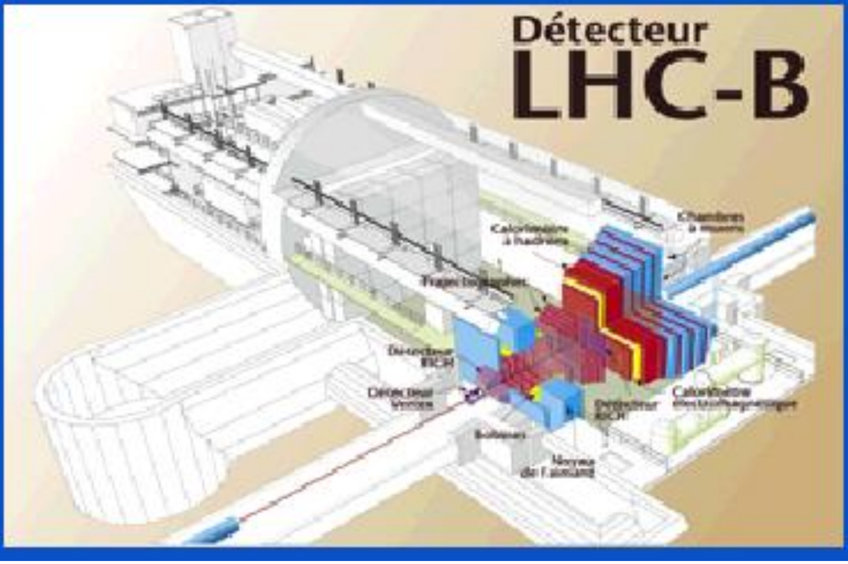


LHC Detectors



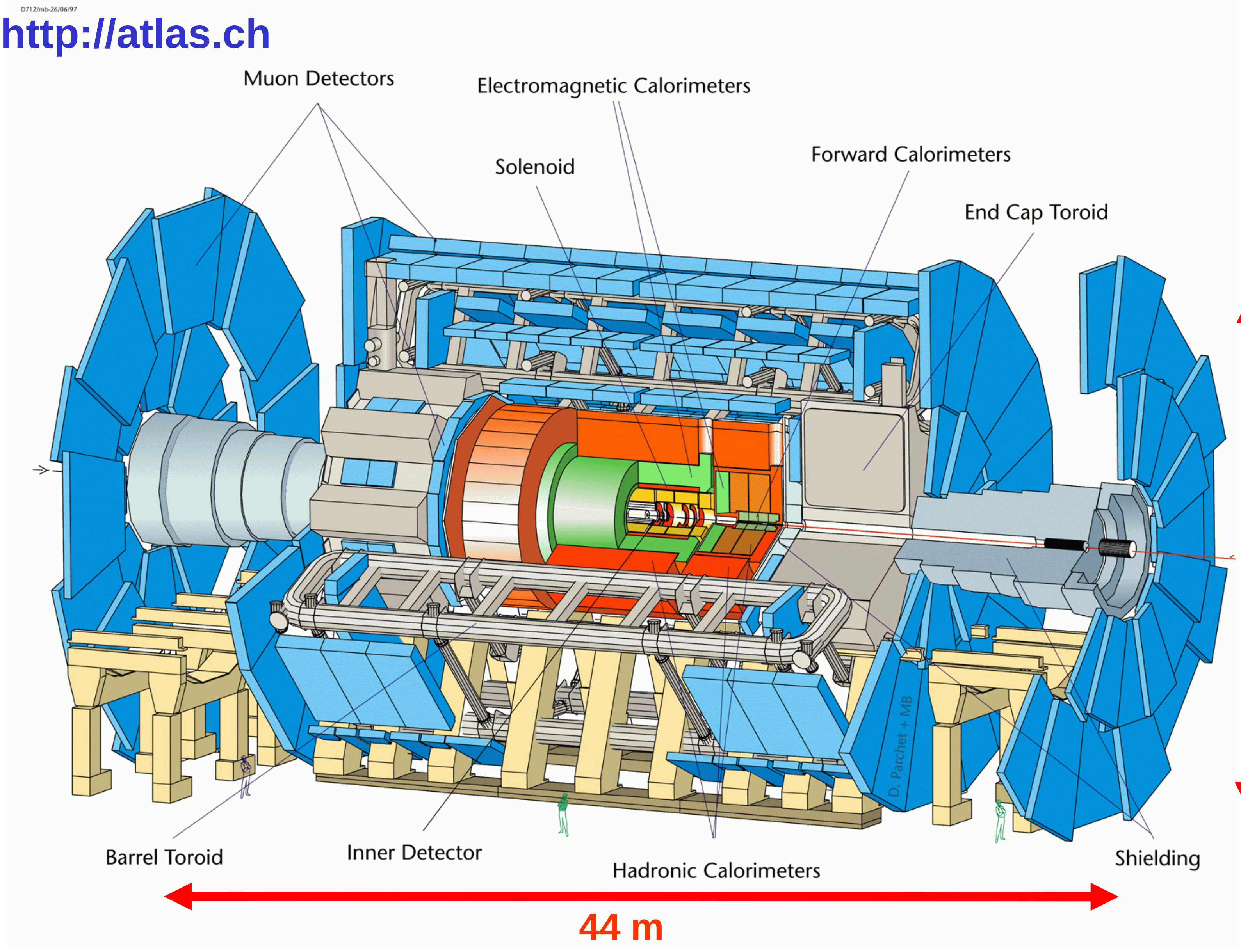


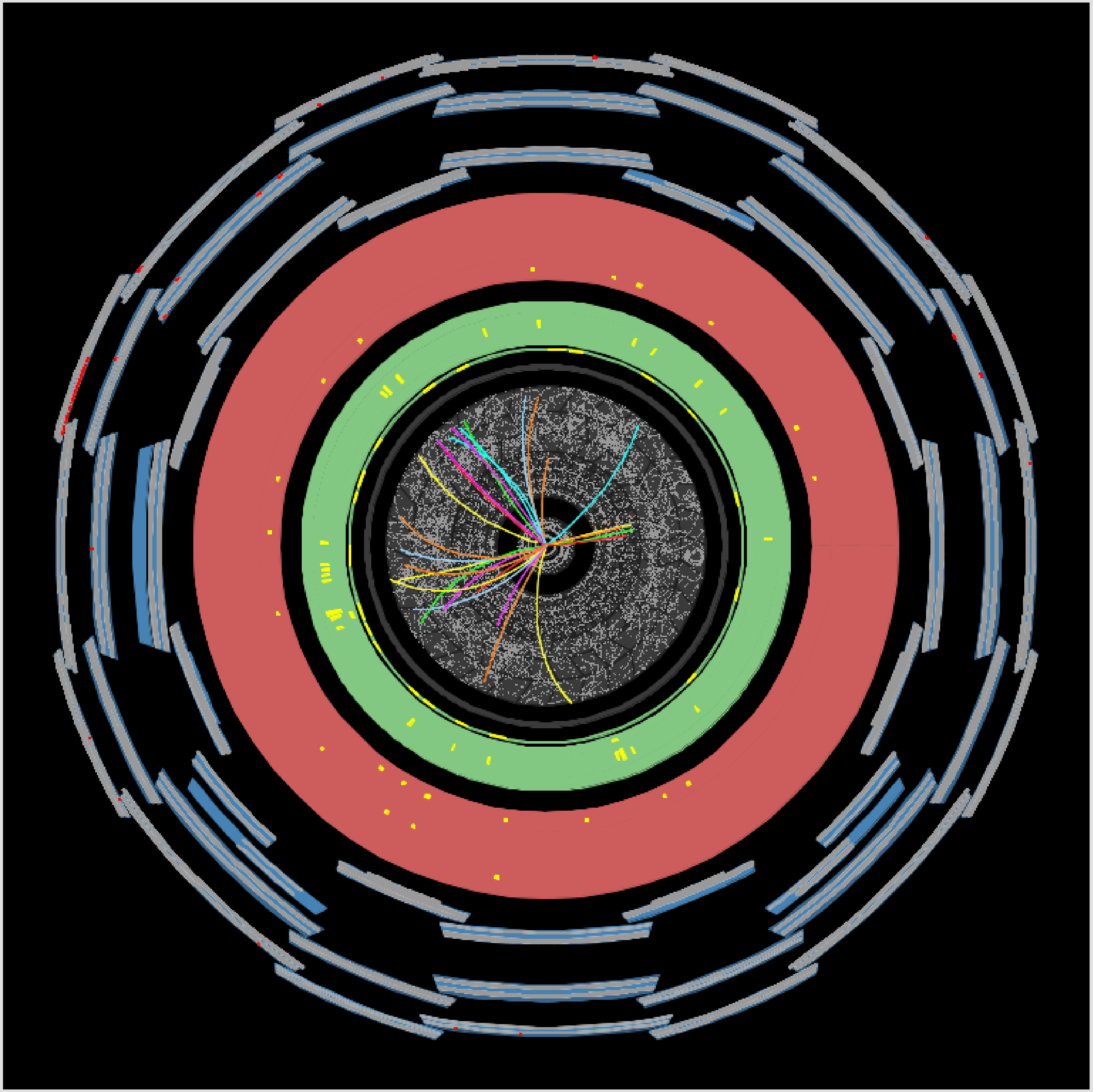


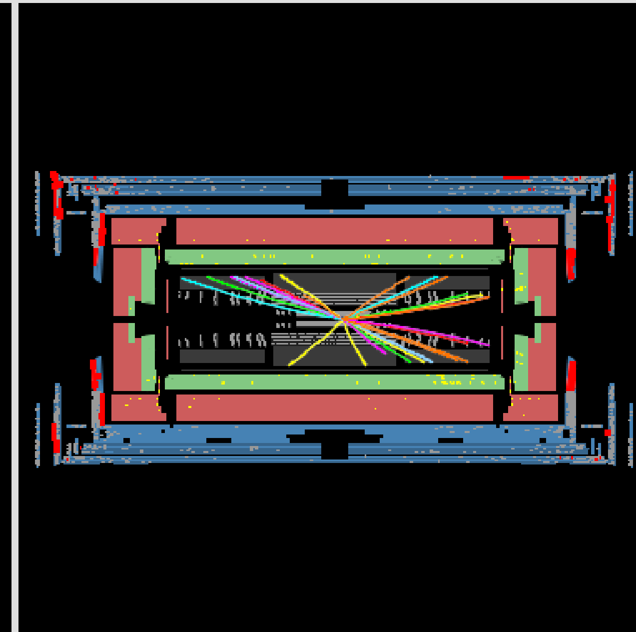


ATLAS Detector at LHC

http://atlas.ch







ATLAS EXPERIMENT

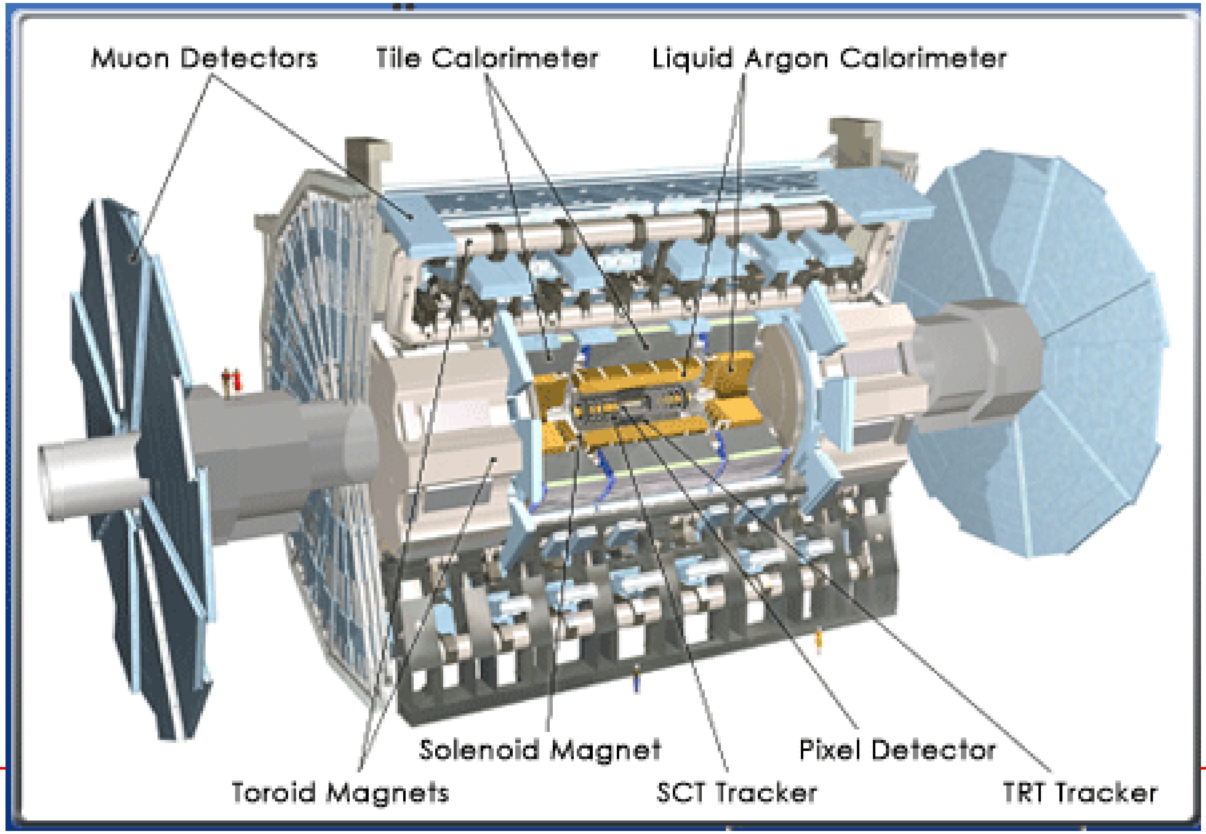
Run Number: 213486, Event Number: 215114913

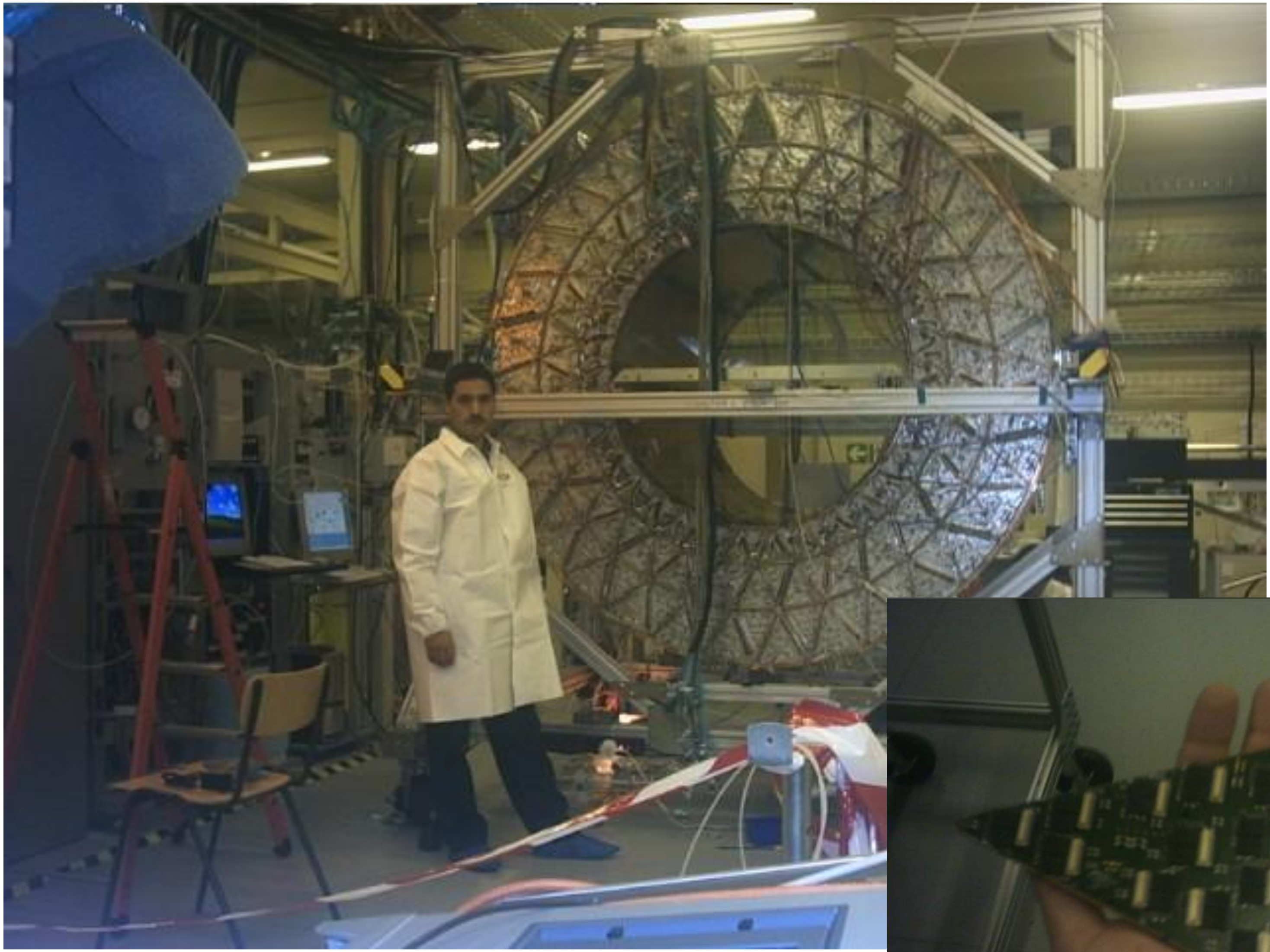
Date: 2012-10-28 04:06:14 CET

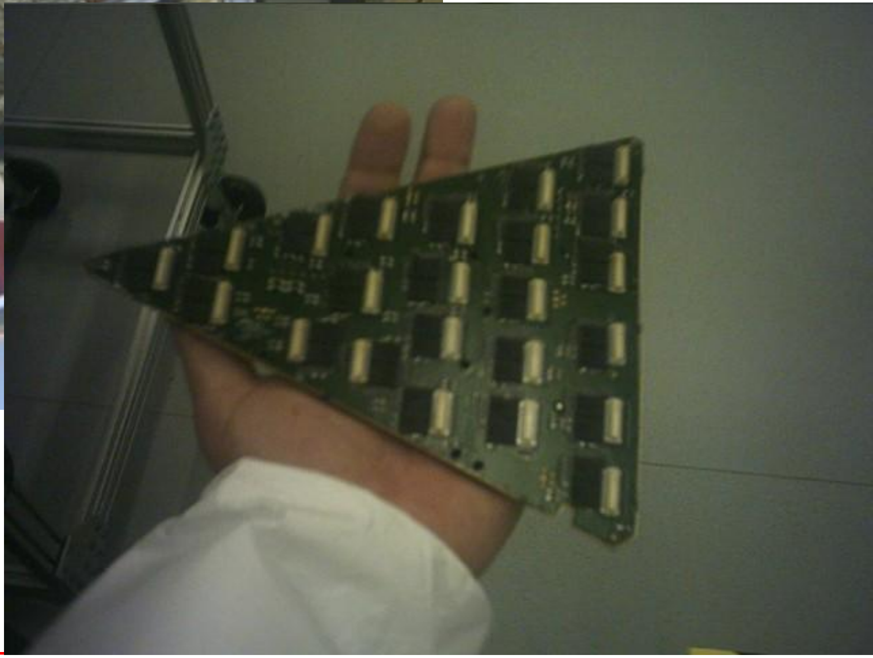
Snapshot of a proton collision
directly from the ATLAS experiment

Four Main Parts of ATLAS

- **Inner tracker**
  Measures the momentum of the charged particles
- **Calorimeter**
  Measures the energies of particles
- **Muon Sepectometer**
  Measures the energy of muons
- **Magnet System**
  Supplies the magnetic field to bend the charged particles for measuresuring p.







9. Exercises

1. Explain the operating principle of the Cherenkov detector.

2. Explain the operating principle of the Calorimeter.

3. (a) A radioactive source emits alpha-particles with kinetic energies of 4 MeV. What must be the value of an applied magnetic field so that the radius of curvature of the orbit of the alpha-particles is 10 cm?
   (b) Do the same calculation for electrons and protons of the same kinetic energy.

4. Estimate the minimum length of a gas (with $n = 1.0003$) Cherenkov counter which could be used in threshold mode to distinguish between pions and kaons with momentum 20 GeV/c. Assume that 200 visible photons (400-700 nm) need to be radiated to ensure a high probability of detection.

5. What are the Cherenkov angles for electrons and pions of 1 GeV/c for a radiator with $n = 1.4$? *What will be the ratio of the number of* radiated photons for incident electrons and pions?

6. If the time resolution of each of two counters (of a TOF detector) that are 2 m apart is 0.2 ns, calculate to better than 10% accuracy the momentum at which the system will just be able to resolve a pion from a kaon.

7. Prove that for a particle in a magnetic field *B* (in Tesla) and having radius *R* (in meter) and charge e, its momenta (in GeV) is given by:

$$p(\mathrm{GeV}) = 0.3BR$$

8. In the figure in Page 11, the measured values $x = 0.1$ m and $L = 1$ m and the magnetic field $B = 1.5$ T are given. Determine the particle momentum *p*.