



MIDDLE EAST TECHNICAL UNIVERSITY

Particle Data Analysis in High Energy Physics

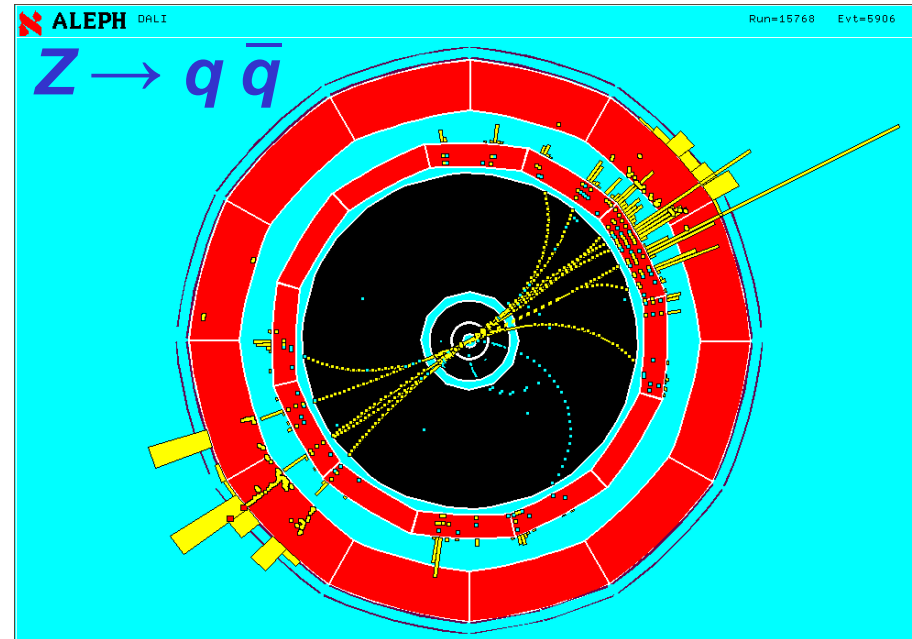
Lecture 6

Accelerators & Detector

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METU, Physics

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Introduction

We will briefly examine the following topics:

Particle Accelerators

Particle Detectors

Particle Accelerators

Interaction of Charged Particles

In particle accelerators we use electric and magnetic fields.

A particle accelerator is a device that uses electric fields to propel ions or charged subatomic particles to high speeds and to contain them in well-defined beams.



An ordinary CRT television set is a simple form of accelerator.



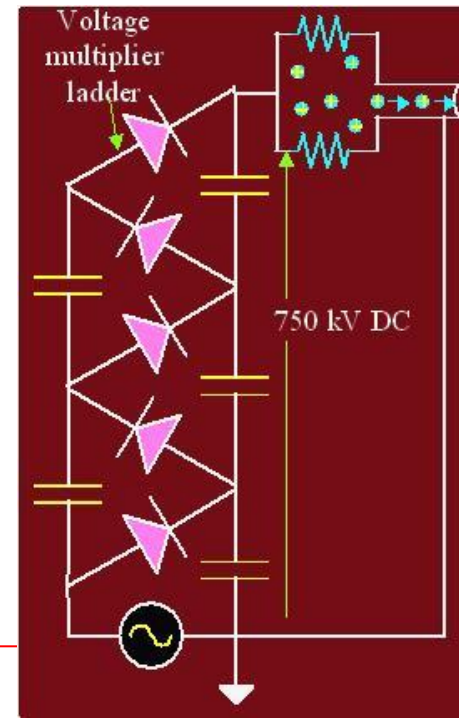
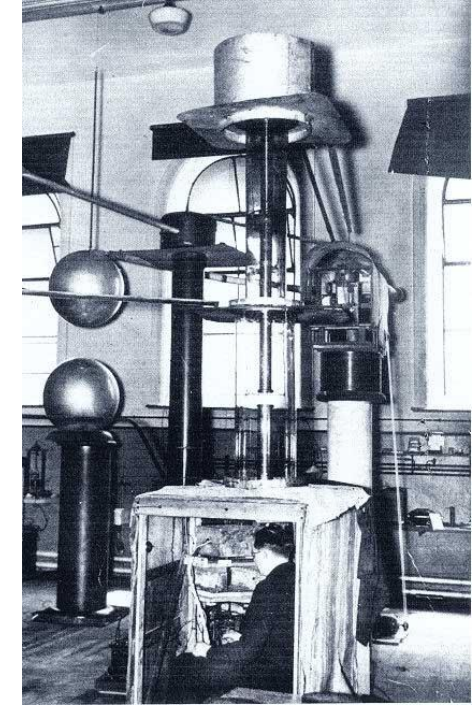
- Accelerators are some of the remarkable tools of modern science.
- They have an important role in *Particle Physics* (PP) and *Nuclear Physics* (NP)
- Nowadays, they are in demand of variety of applications:
 - *Condensed matter Physics*
 - *Electronic industry*
 - *Biomedical areas*
 - *Geophysical areas*
 - *Food processing*
 - *Sewage treatment*

- **In PP and NP we have to consider**
 - the required energies of particles
 - the desired beam intensity
 - the economic constraints

- **Basically accelerators can be categorised in two types**
 - *Linear accelerators (Linac)*
 - *Circular accelerators*

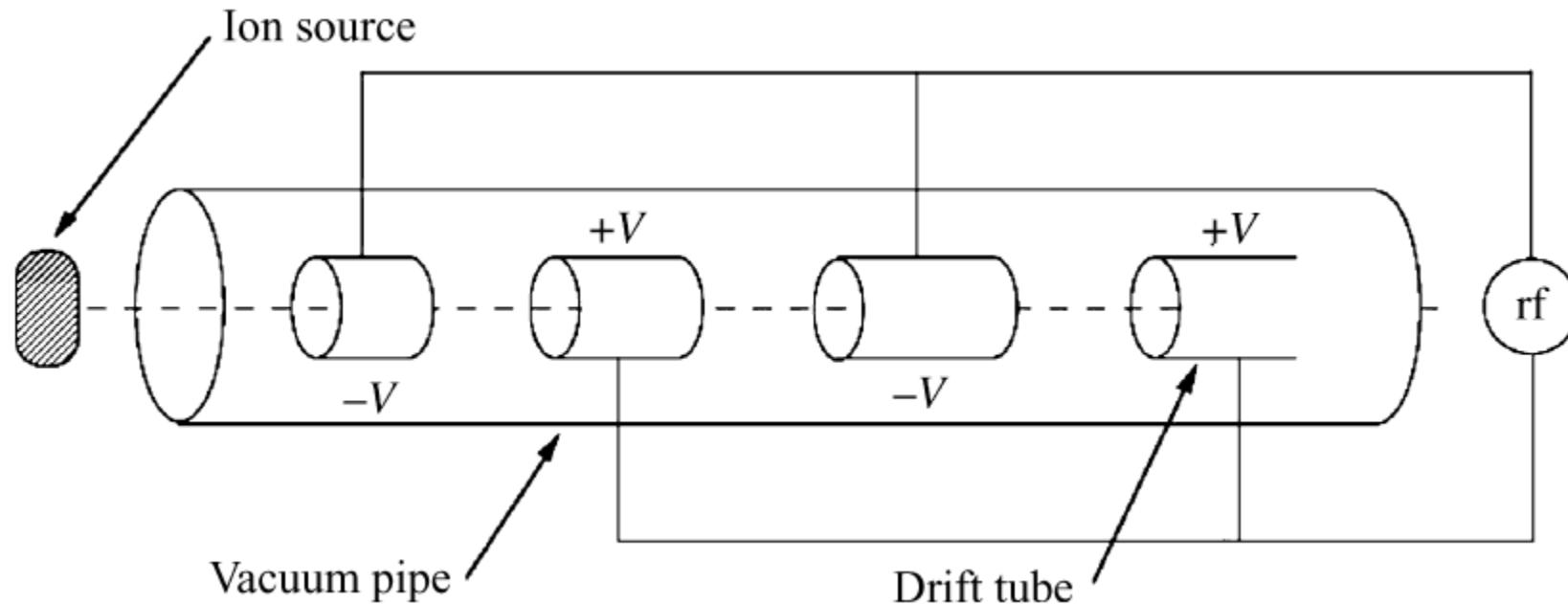
Cockroft-Walton Machine

- First high voltage particle acc. (developed 1930s)
- Voltage-doubling circuits were used (~ 100 kV)
- Based on passing ions through sets of aligned electrodes operated at successively higher fixed potentials
- They won Nobel prize for “*Transmutation of atomic nuclei by artificially accelerated atomic particles*”



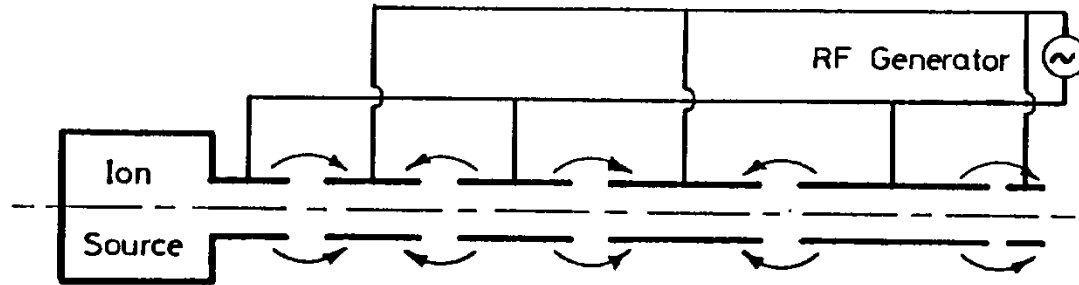
Linear Accelerators

- In a linear accelerator (or linac) for accelerating ions, particles pass through a series of metal pipes called **drift tubes**, that are located in a vacuum vessel and connected successively to alternate terminals of an R.F. oscillator.



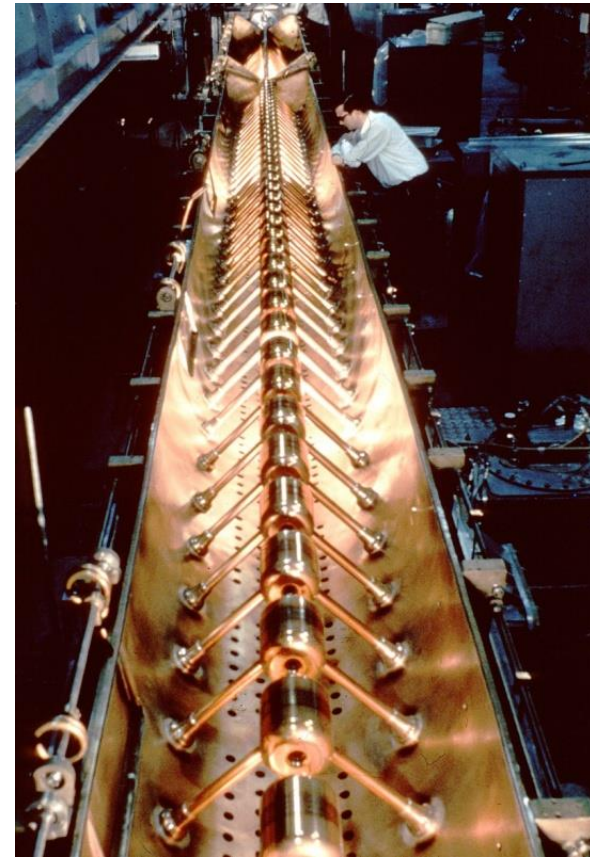
<https://www.youtube.com/watch?v=3Bm60Hdvl6s>

- Energy is gained by RF cavities



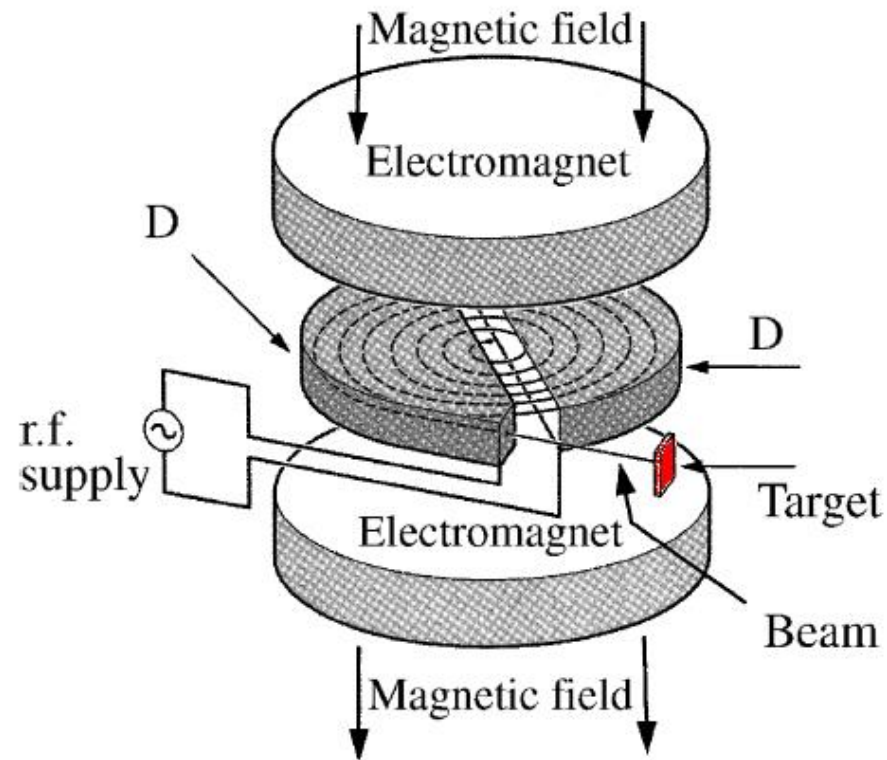
SLAC - Stanford Linear Accelerator Center

- Total length = 3.2 km
- 100,000 RF cavity
- $E_{cm} = 50 \text{ GeV}$ (electron)

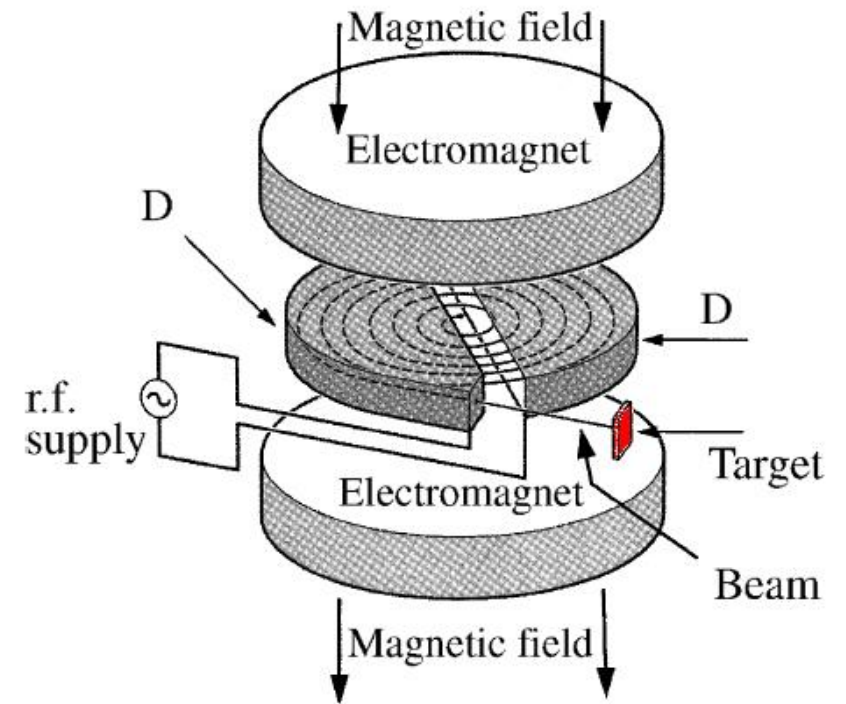


Cyclotrons

- Circular (or Cyclic) accelerators used for low-energy nuclear physics experiments are of a type called **cyclotrons**.
- They are also used to produce beams of particles for medical applications, including proton beams for radiation therapy.



- The accelerator consists of two 'D'-shaped sections across which an r.f. electric field is established.
- Charged ions are injected into the machine near its centre and are constrained to traverse outward in spiral trajectories by a magnetic field.
- The ions are accelerated each time they pass across the gap between the dees.
- At the maximum radius, which corresponds to the maximum energy, the beam is extracted to hit a target



<https://www.youtube.com/watch?v=VAqjyQC4zwk>

LEP (Large electron-positron Collider)

- LEP was one of the largest particle accelerators ever constructed.
- It was built at CERN.
- The results of the LEP experiments allowed precise values of many quantities of the Standard Model, such as W and Z bosons.

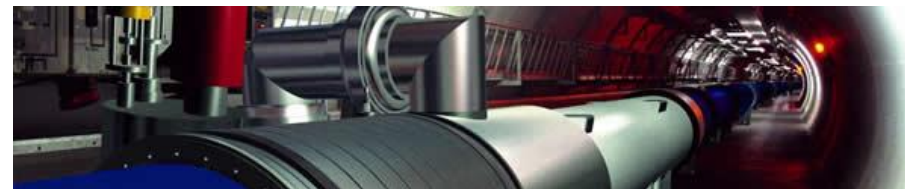
Some properties

- Circumference = 27 km
- About ~100 m underground
- 1989-1995: Z boson precision measurement at $E_{\text{CM}} = m_Z c^2 = 91.2 \text{ GeV}$
- 1995-2000: W^\pm boson precision measurement at $E_{\text{CM}} = 2m_W c^2 = 160 \text{ GeV}$

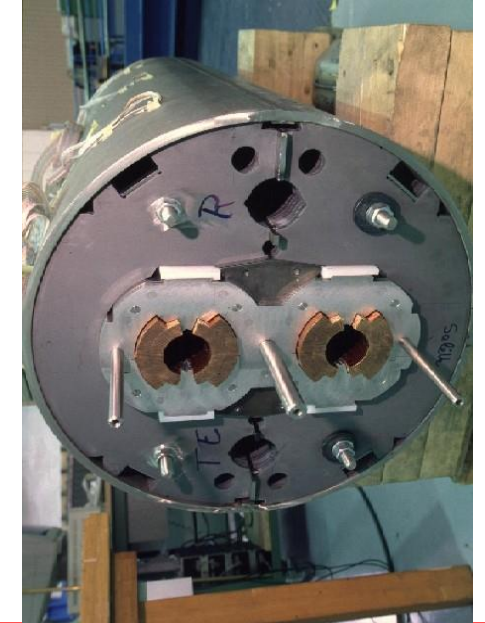
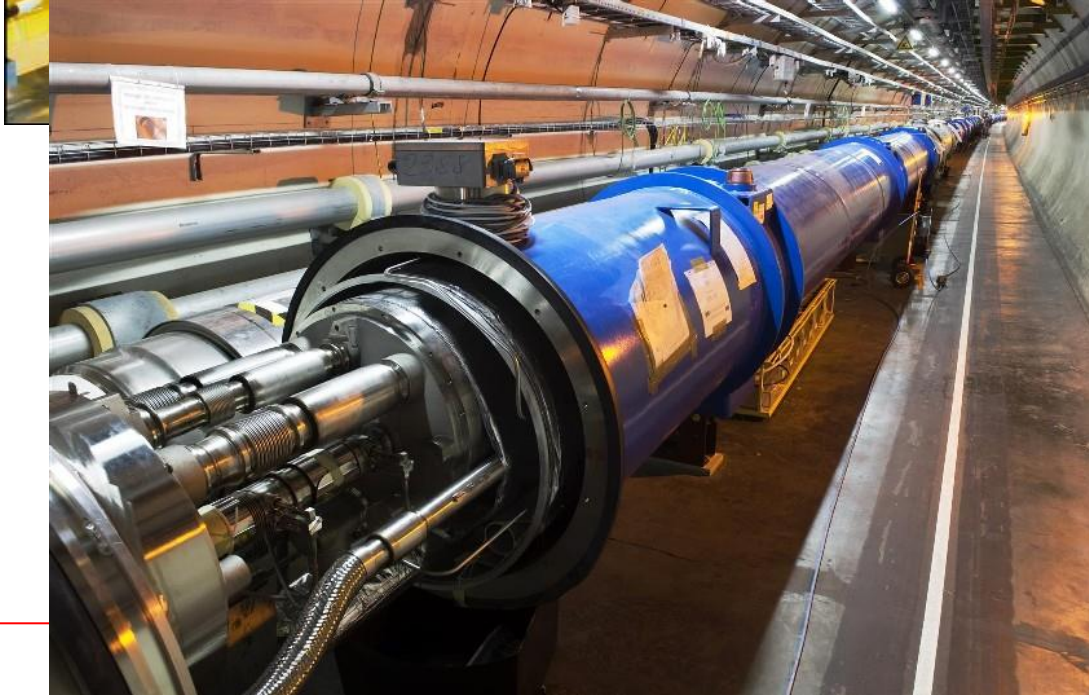


LHC: Large Hadron Collider

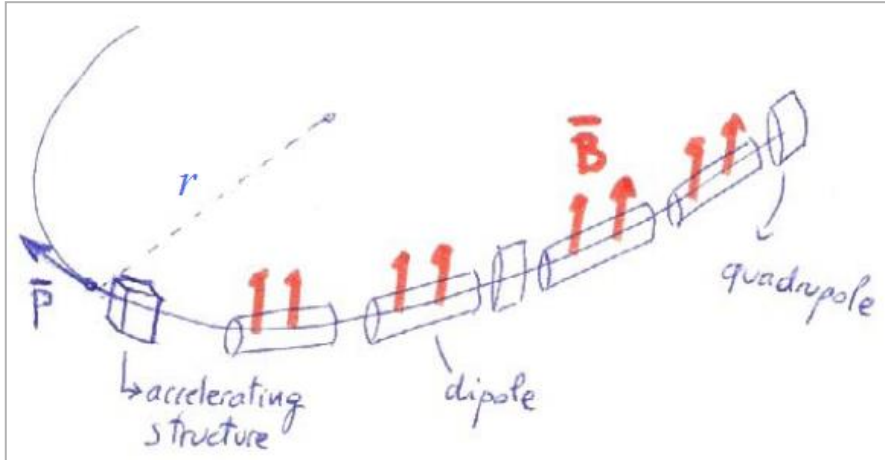
- **Large** : circumference = 27 km
Hadron: accelerated particles
 - protons with $E_{cm} = 14 \text{ TeV}$
 - Pb ions with $E_{cm} = 1150 \text{ TeV}$
(82 p ve 125 n)
- LHC project:
 - Idea: December 1994
 - LEP is converted to LHC
 - Started at September 2008
 - Cost: 3 billion €
 - Web: lhc.web.cern.ch







Why Large?



Centripetal Force: $F = mv^2/r$

Lorentz Force: $F = evB$

Relativistic Dynamics:

$$p = \gamma mv \quad \gamma = (1 - v^2/c^2)^{-1/2}$$

$$F = \frac{dp}{dt} = \gamma m \frac{dv}{dt} = \gamma m \frac{v^2}{r} = evB$$

Momentum: $p = eBr$

Total Energy: $E = \sqrt{p^2 c^2 + m^2 c^4}$

Ultra-relativistic limit: $E \approx pc = ecBr$

$$E(\text{GeV}) = 0.3Br$$

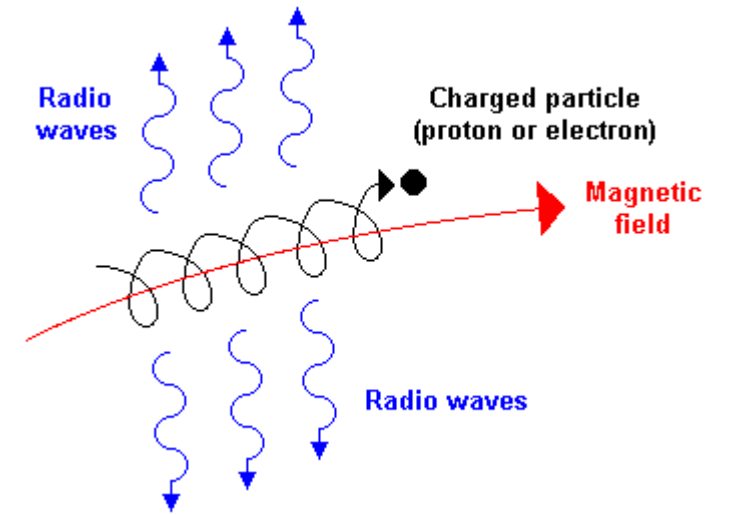
Therefore, energy gained by the particle is proportional to radius of curvature

Why Large?

Synchrotron radiation is the name given to the radiation which occurs when charged particles are accelerated in a curved path or orbit.

Classically, any charged particle which moves in a curved path **or** is accelerated in a straight-line path will emit electromagnetic radiation.

Particularly in the application to circular particle accelerators like synchrotrons, the radiation is referred to as synchrotron radiation.



Why Large?

The large circumference is preferred to keep the synchrotron radiation to a practical level.

The rate of energy loss being inversely proportional to the radius of curvature.

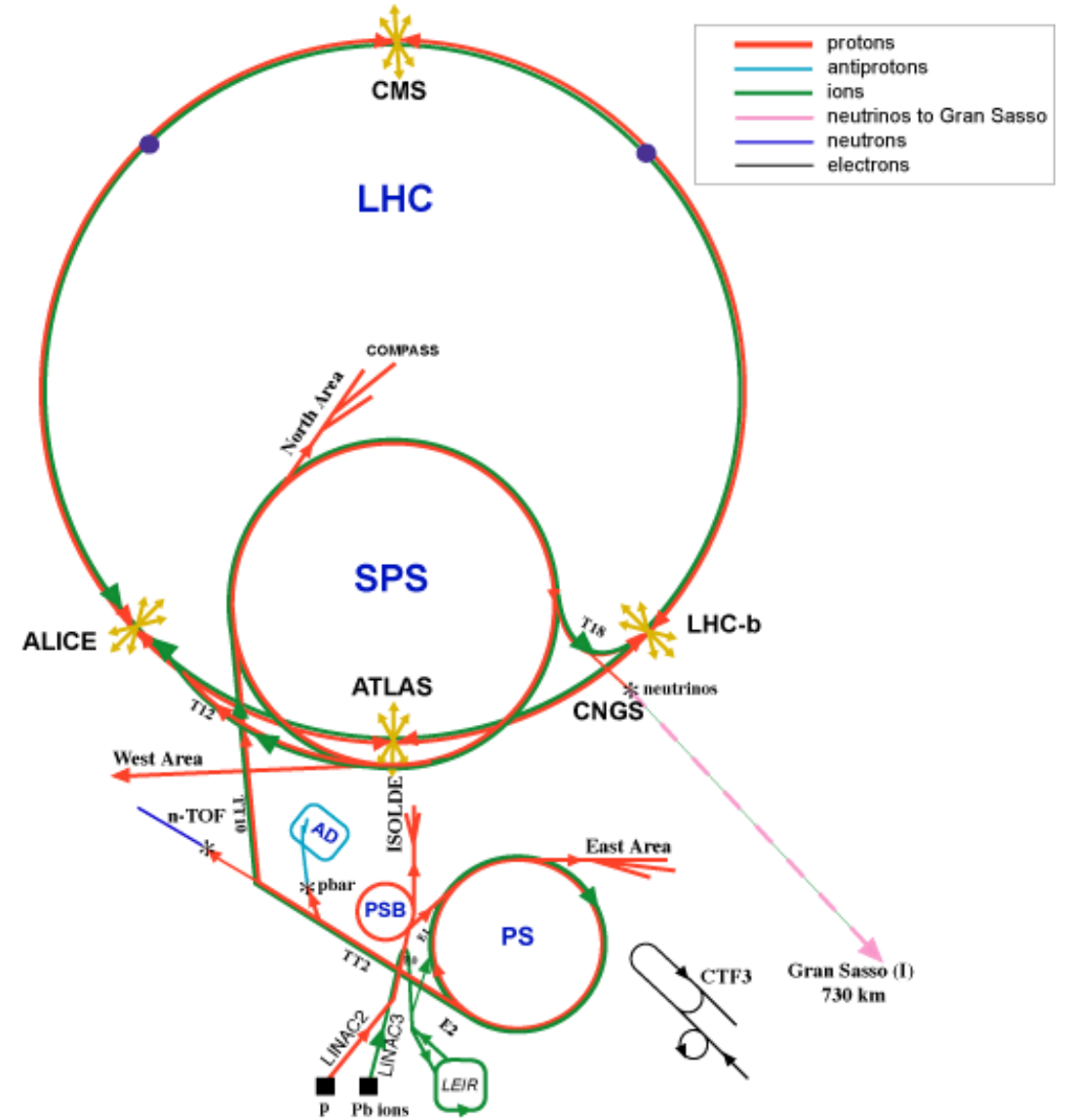
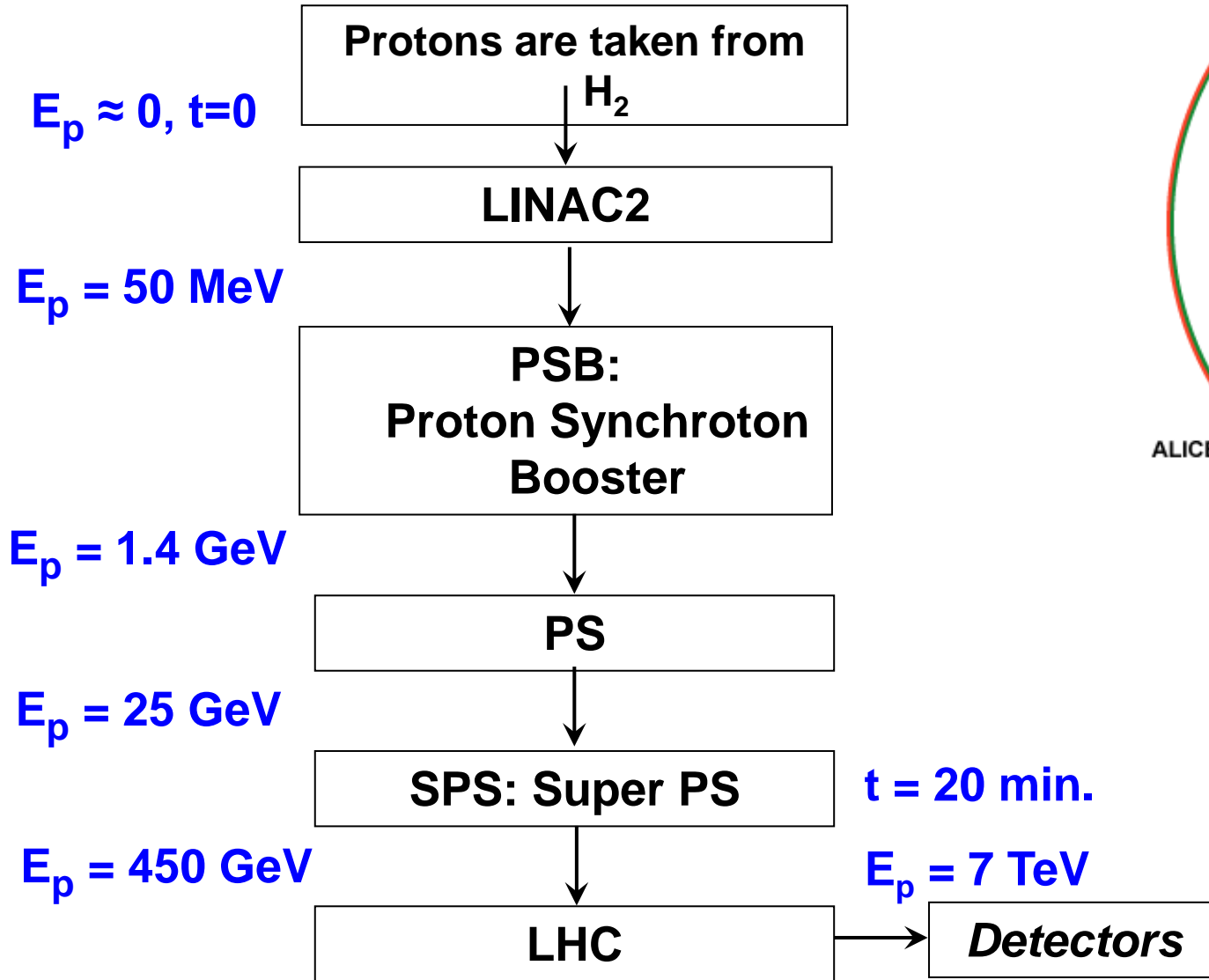
Under the circular acceleration, an particles emits synchrotron radiation, the energy radiated (power lost) per particle per turn is:

$$P = \frac{2ke^2\gamma^4v^4}{3c^3r^2}$$

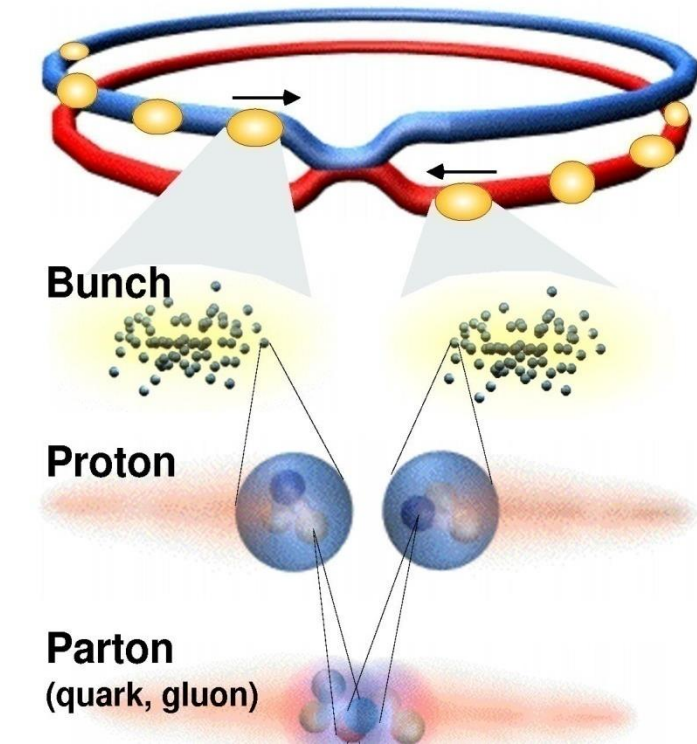
The loss of energy per orbit (turn) can be calculated from:

$$\Delta E = PT = P \left(\frac{2\pi r}{v} \right) = \frac{4\pi ke^2\gamma^4\beta^3}{3r}$$

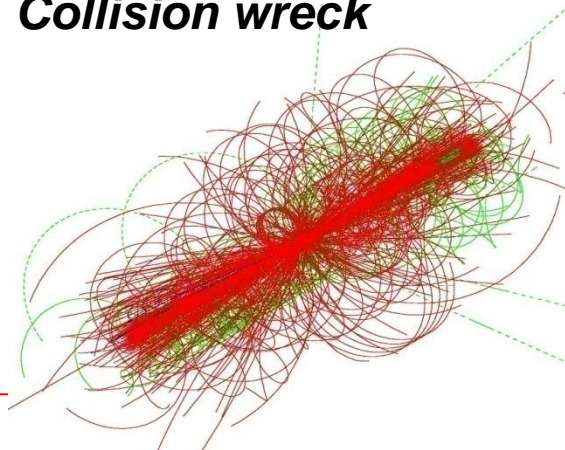
LHC Complex



About p-p collision at LHC



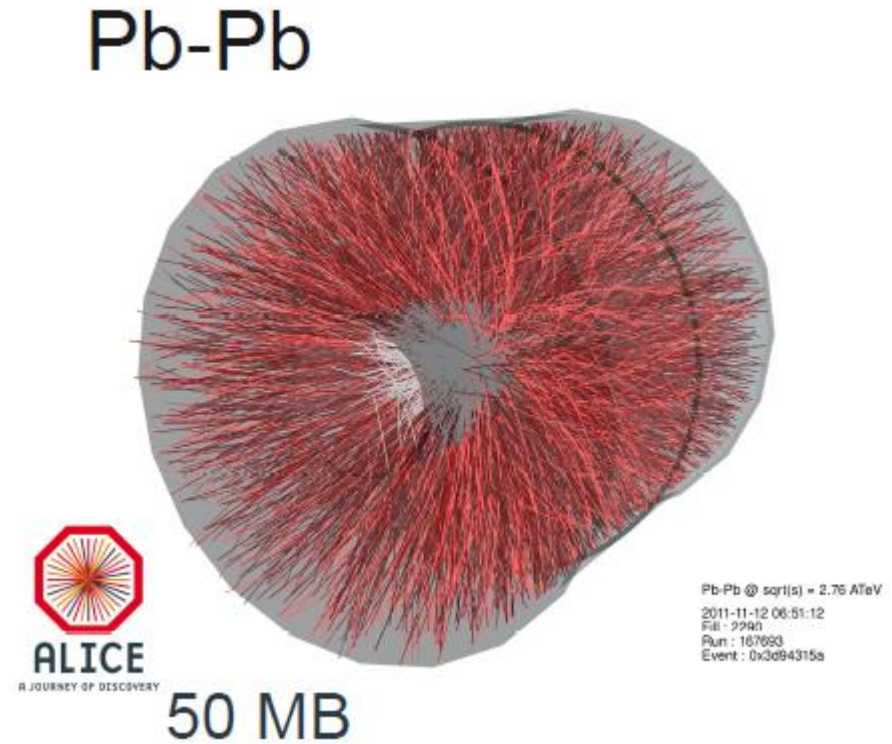
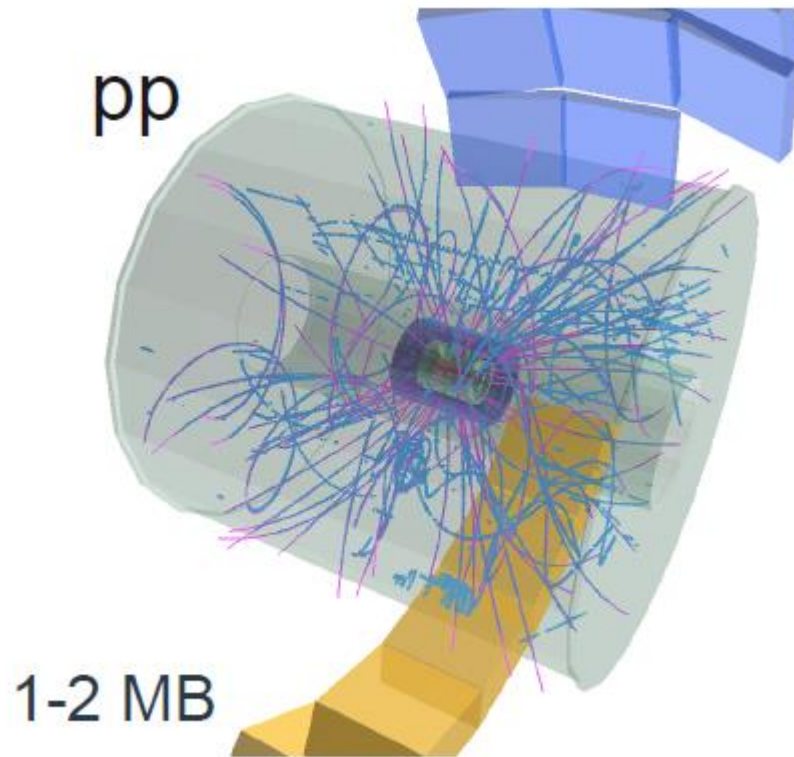
Collision wreck



- Maximum CM collision energy: $E_{\text{cm}} = 14 \text{ TeV}$
- Total number of bunch: 2808×2808
- Bunch diameter: $D = 16 \mu\text{m}$ (hair $50 \mu\text{m}$)
- Number of particles per bunch: $N = 10^{11}$
- Luminosity: $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Distance between two bunches: $d = 7.5 \text{ m}$
- Cross-over rate: $t = 25 \text{ ns}$
- Collision frequency
 $f = 1/25 \text{ ns} = 40,000,000 \text{ Hz} = 40 \text{ MHz}$
- Number of head on collision per bunch is 20

Event Size

Event size depends on the number of particles produced in the collision!

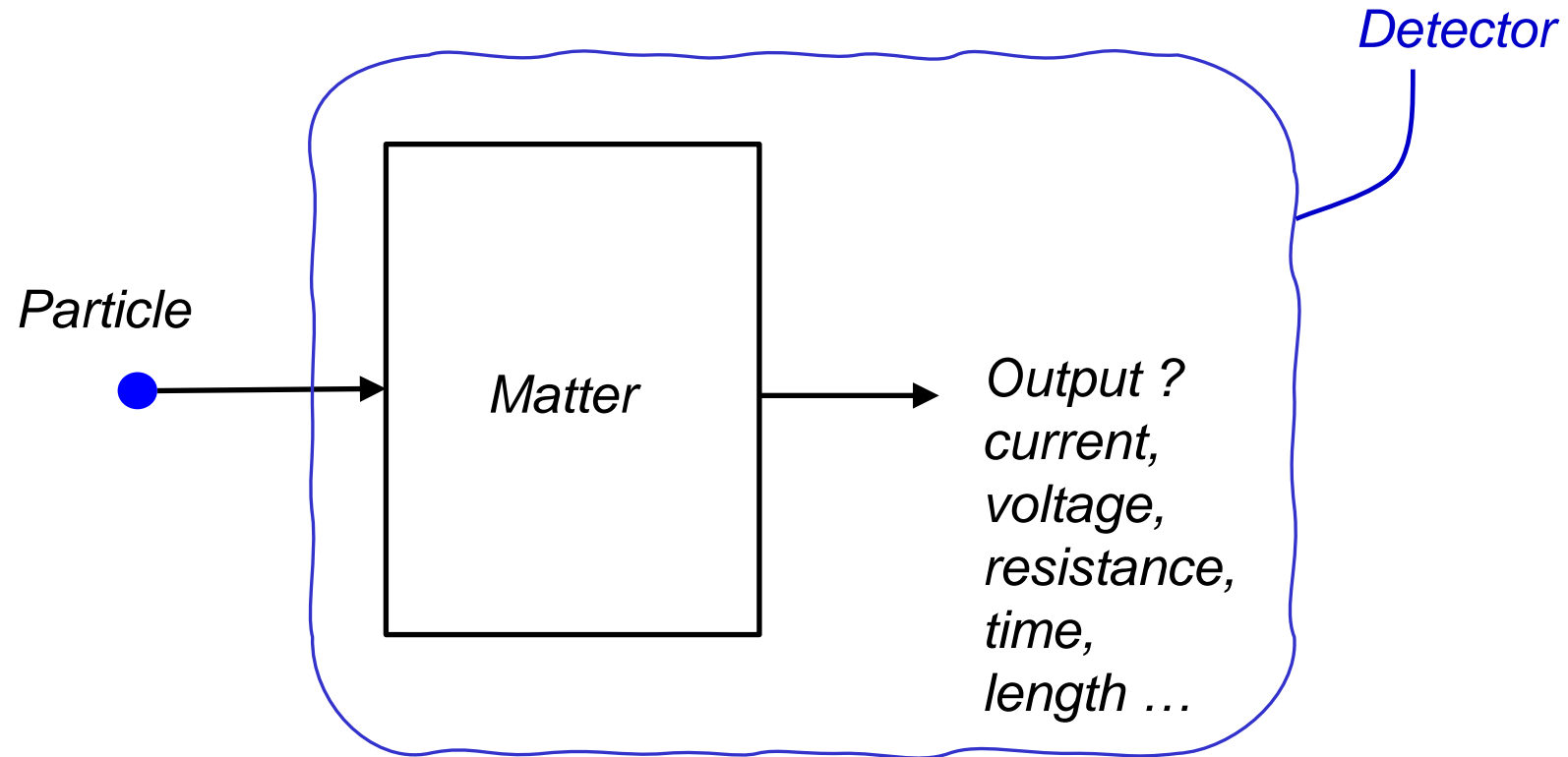


Particle Detectors

Detector

To detect (see) a particle,

1. it must interact with matter
2. it must result in a measurable quantities in detection system

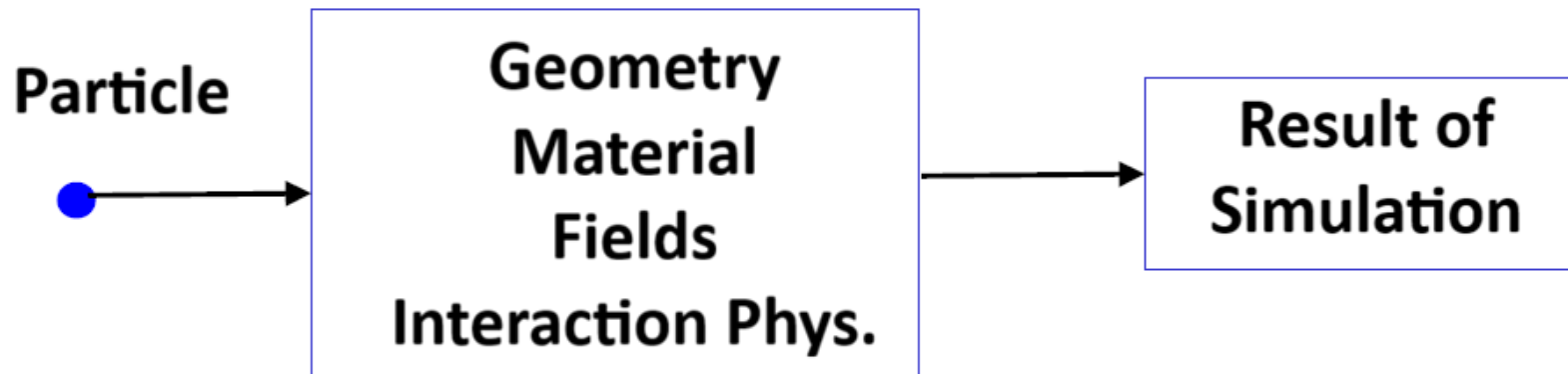


Detector Simulation

In the Simulation of particle detectors we use theoretical calculations.

Inputs: 4-vector of particle(s), material and geometry, E-B Fields, interaction physics

Outputs: Identity and 4-vector of particle(s), location and value of energy deposition in media, new particles, ...

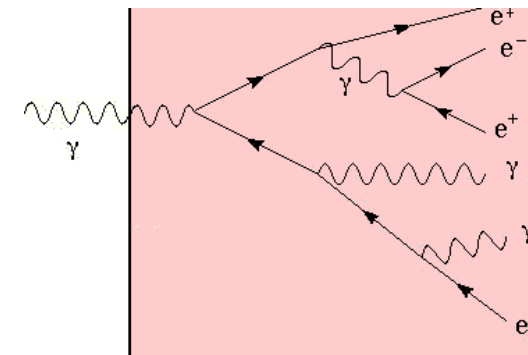
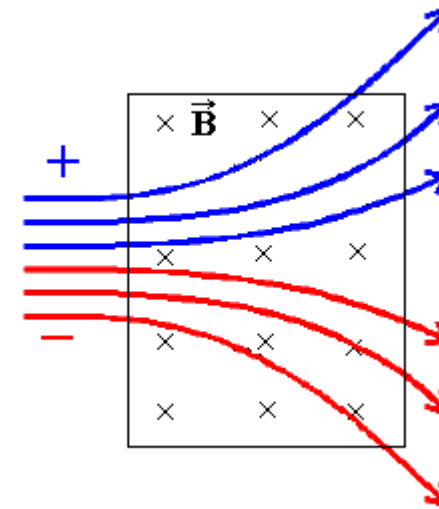


Professional Simulation Programs: [Geant4](#), [Fluka](#), [MCNP](#), [Phits](#)

Detectors employed in HEP experiments record
position, arrival time, momentum, energy and identity
of particles.

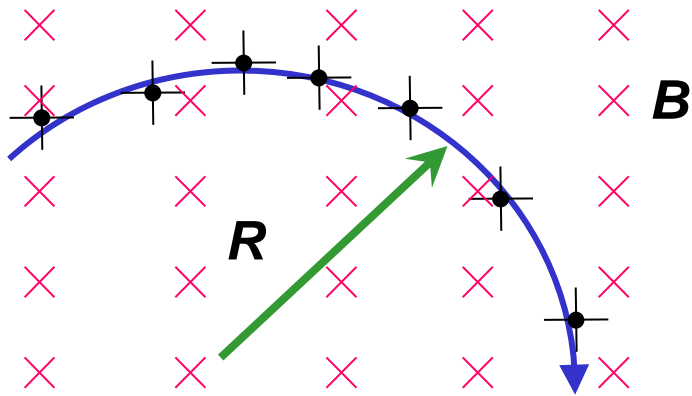
Charged particles (e^\pm p K^\pm μ^\pm π^\pm)
can be detected through their ionisation in tracking chambers
* a measure of the curvature of the track in a magnetic field
gives a measure of its momentum
* a measure of the rate of ionisation loss (dE/dx) can be used
to determine its type

Neutral particles (γ n)
are detected via calorimeters, where their position
and energy are measured.

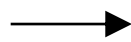


We need charged particle tracking system in HEP experiments to determine

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



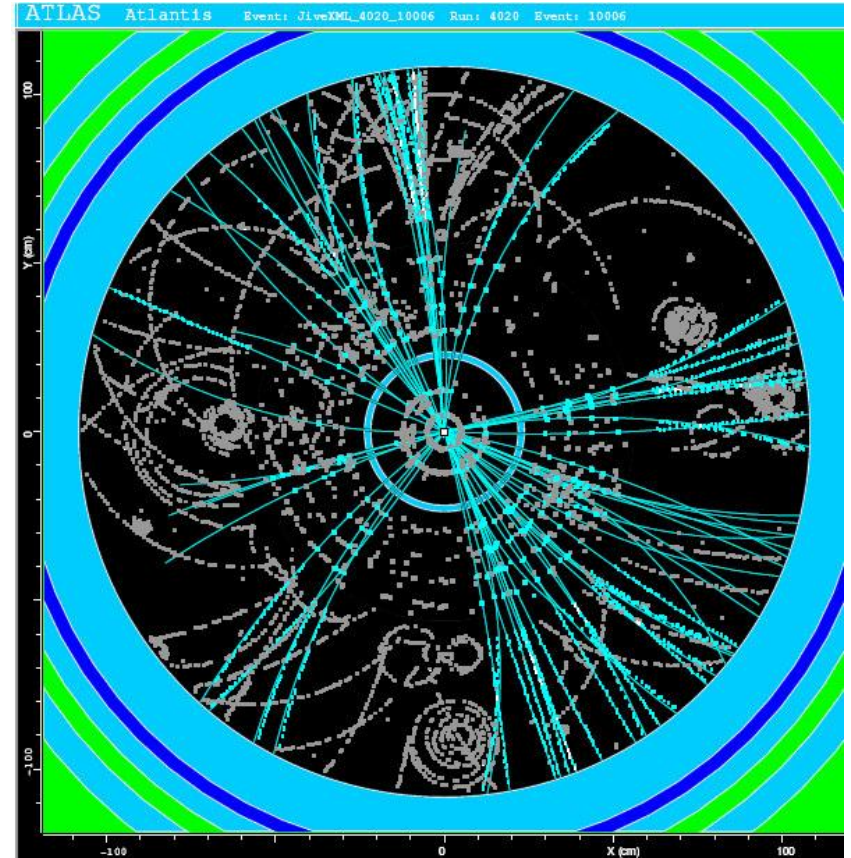
$$\frac{mv^2}{R} = qvB$$



$$p = mv = BqR$$

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

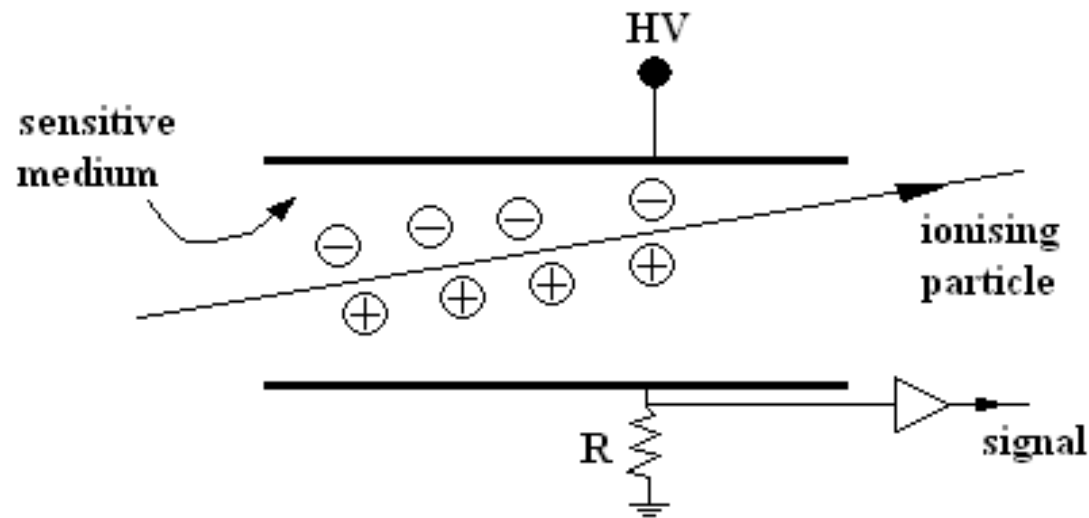
B in Tesla and R in meter



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.

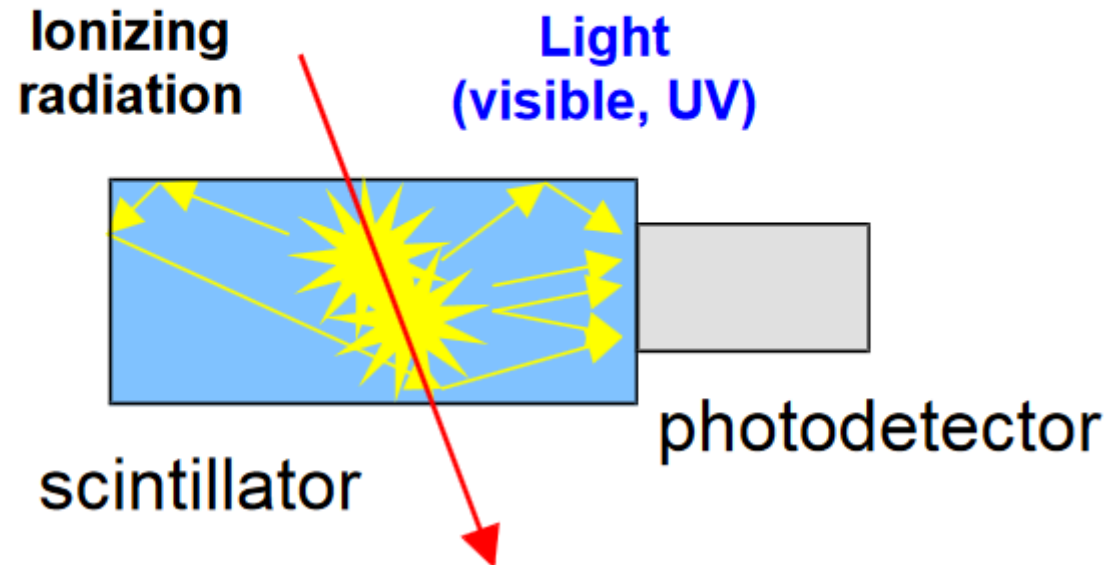
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)}\right) - \beta^2 \right]$$



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.

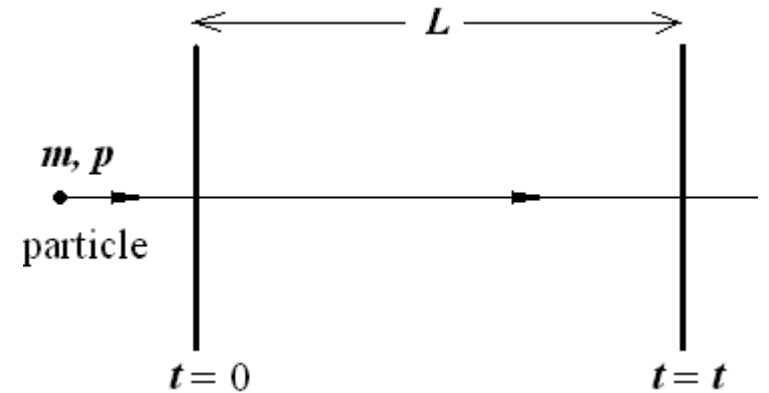


Time of Flight Detectors

- 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 particles with momenta less than about $p = 4 \text{ GeV}/c$

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

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



- For two different particles with the same momentum p time difference is

$$\begin{aligned} \Delta t = t_2 - t_1 &= \frac{L}{v_2} - \frac{L}{v_1} = \frac{L}{c} \left(\frac{1}{\beta_2} - \frac{1}{\beta_1} \right) \\ &= \frac{L}{c} \left(\frac{E_2}{pc} - \frac{E_1}{pc} \right) = \frac{L}{pc^2} ([m_2^2 c^4 + p^2 c^2]^{1/2} - [m_1^2 c^4 + p^2 c^2]^{1/2}) \end{aligned}$$

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

measured mass:

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

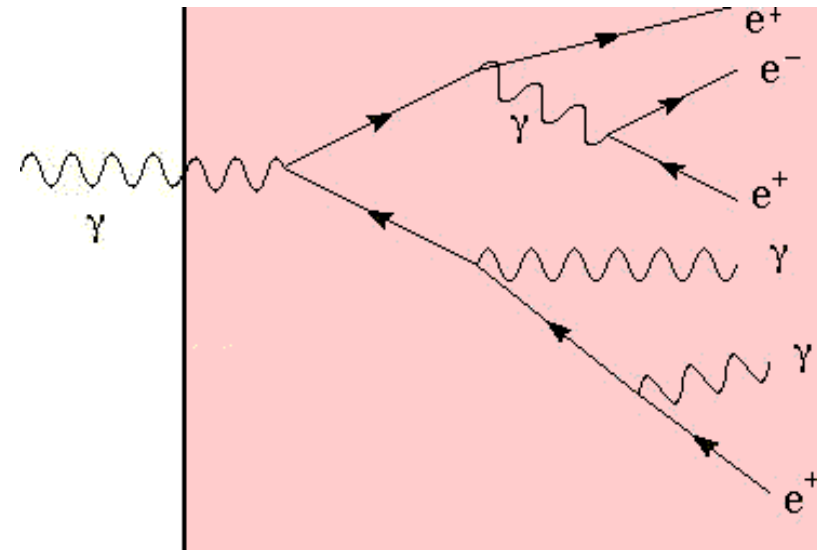
mass resolution:

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

Calorimeters

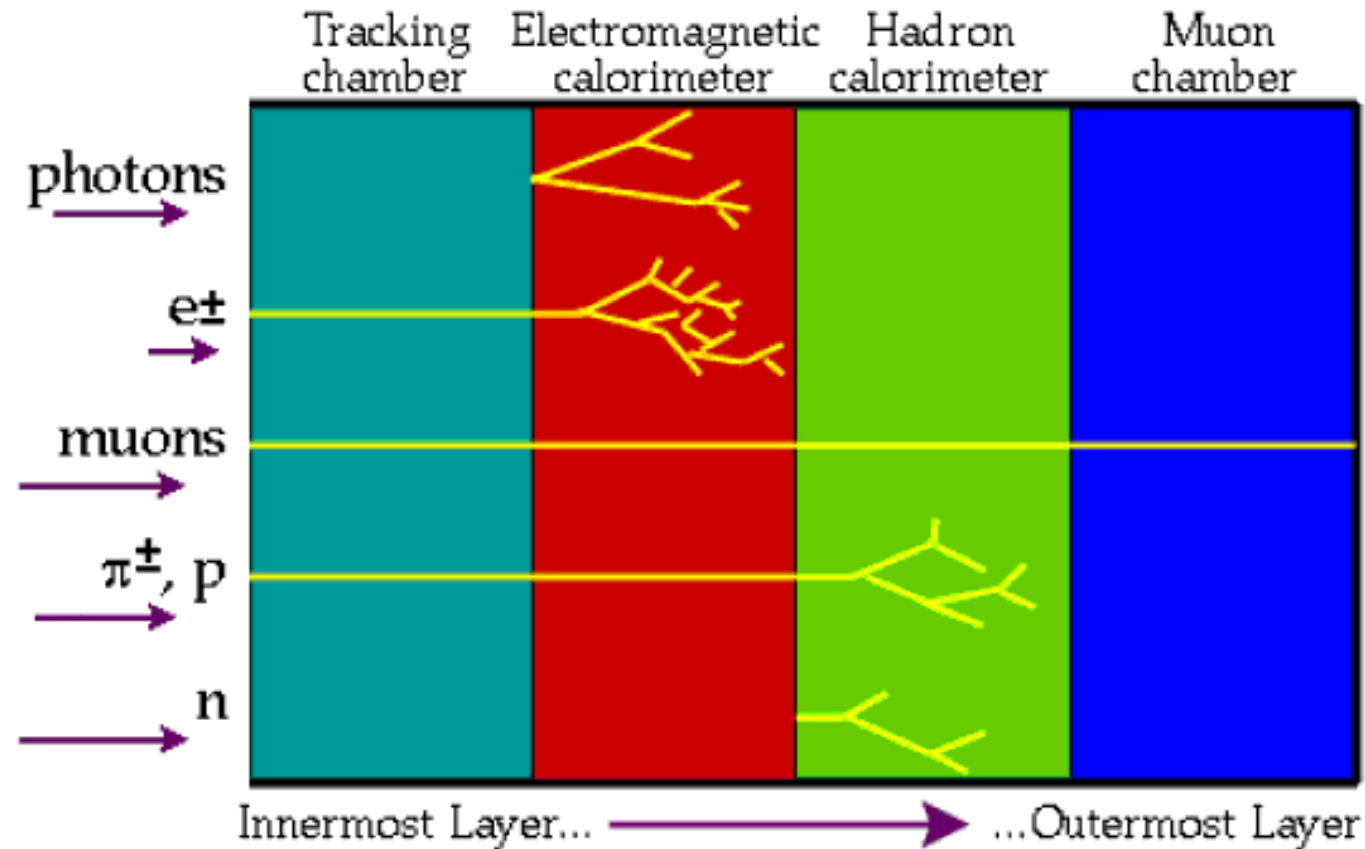
For **electrons** and **photons** of high energy, a dramatic result of the combined phenomena of bramsstrahlung and pair production is the occurrence of cascade showers.

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.

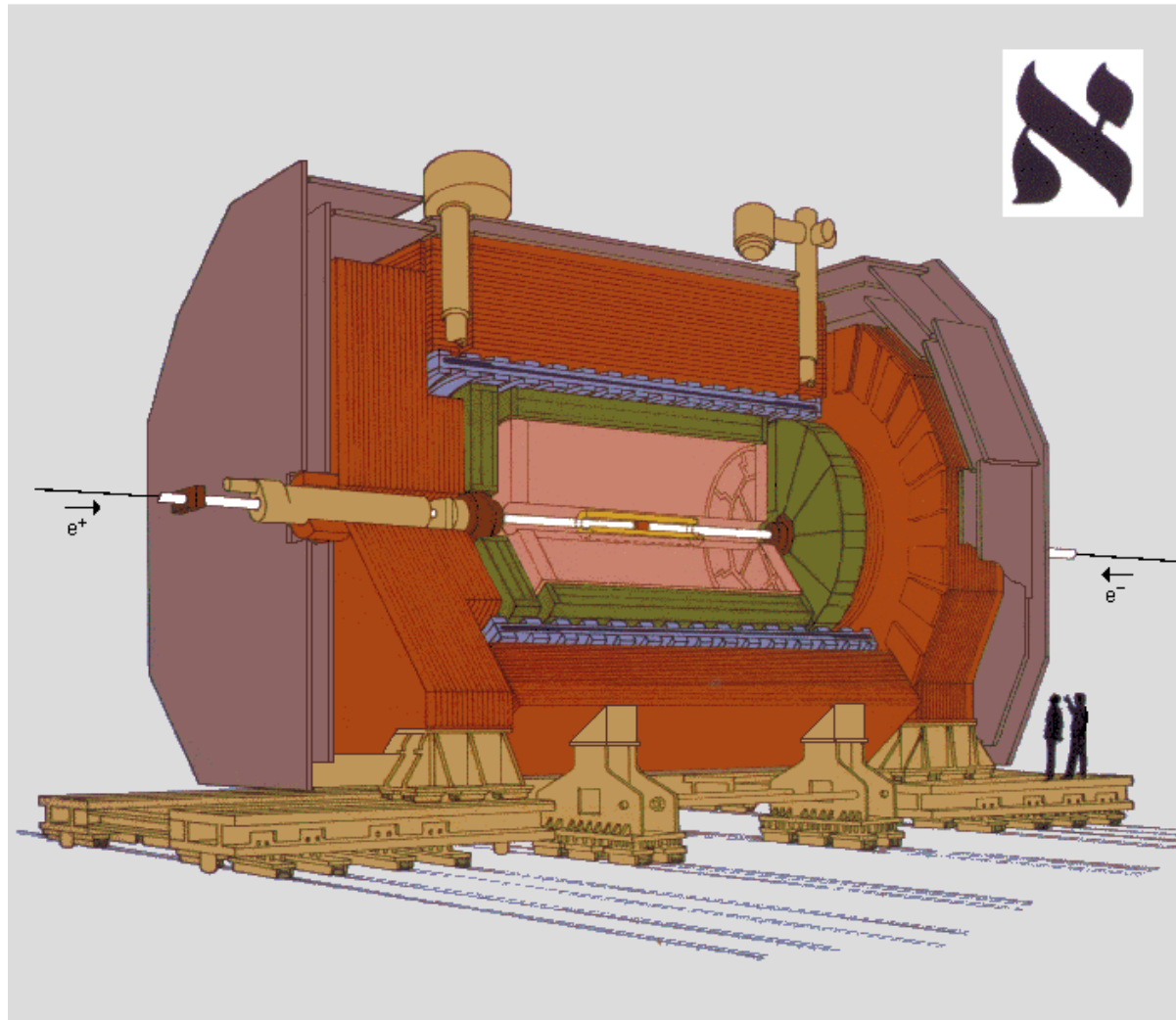


Big Detectors

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

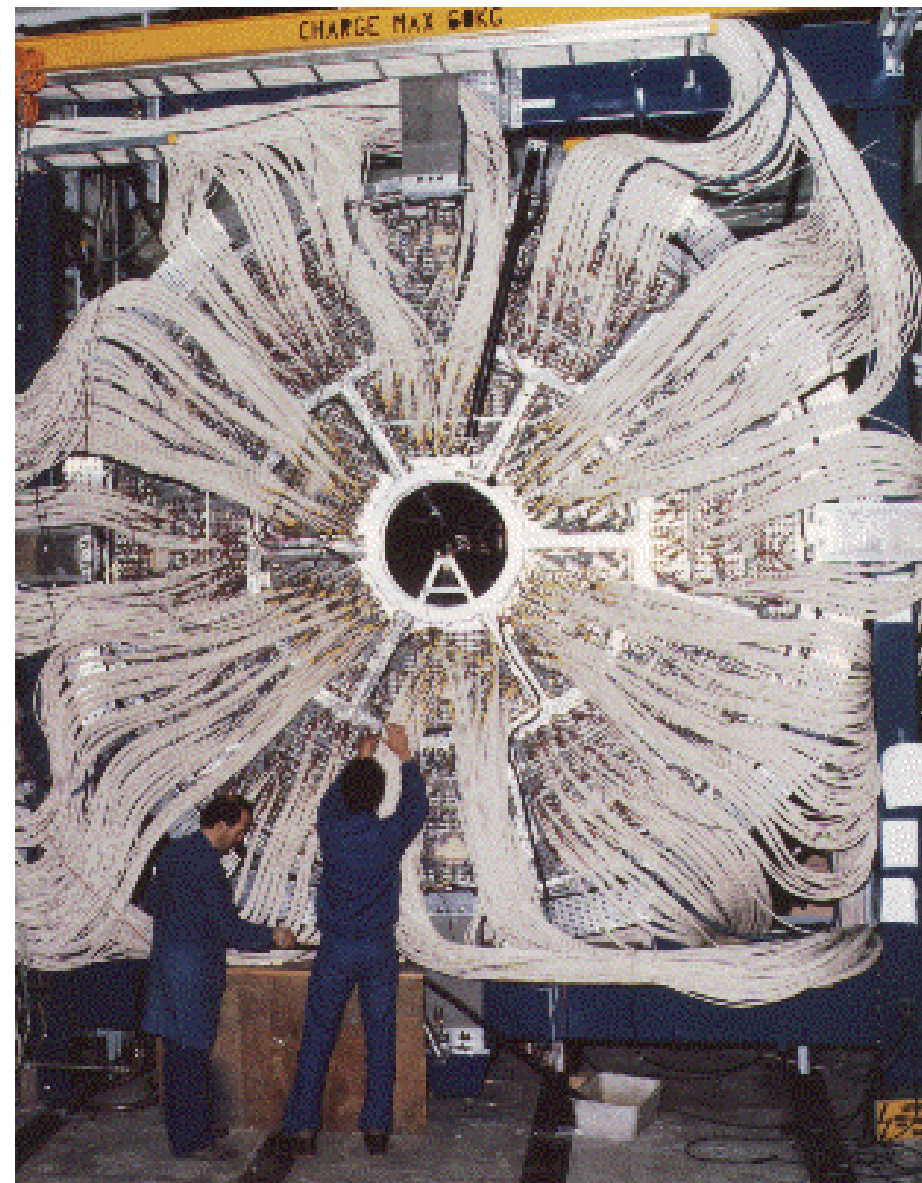
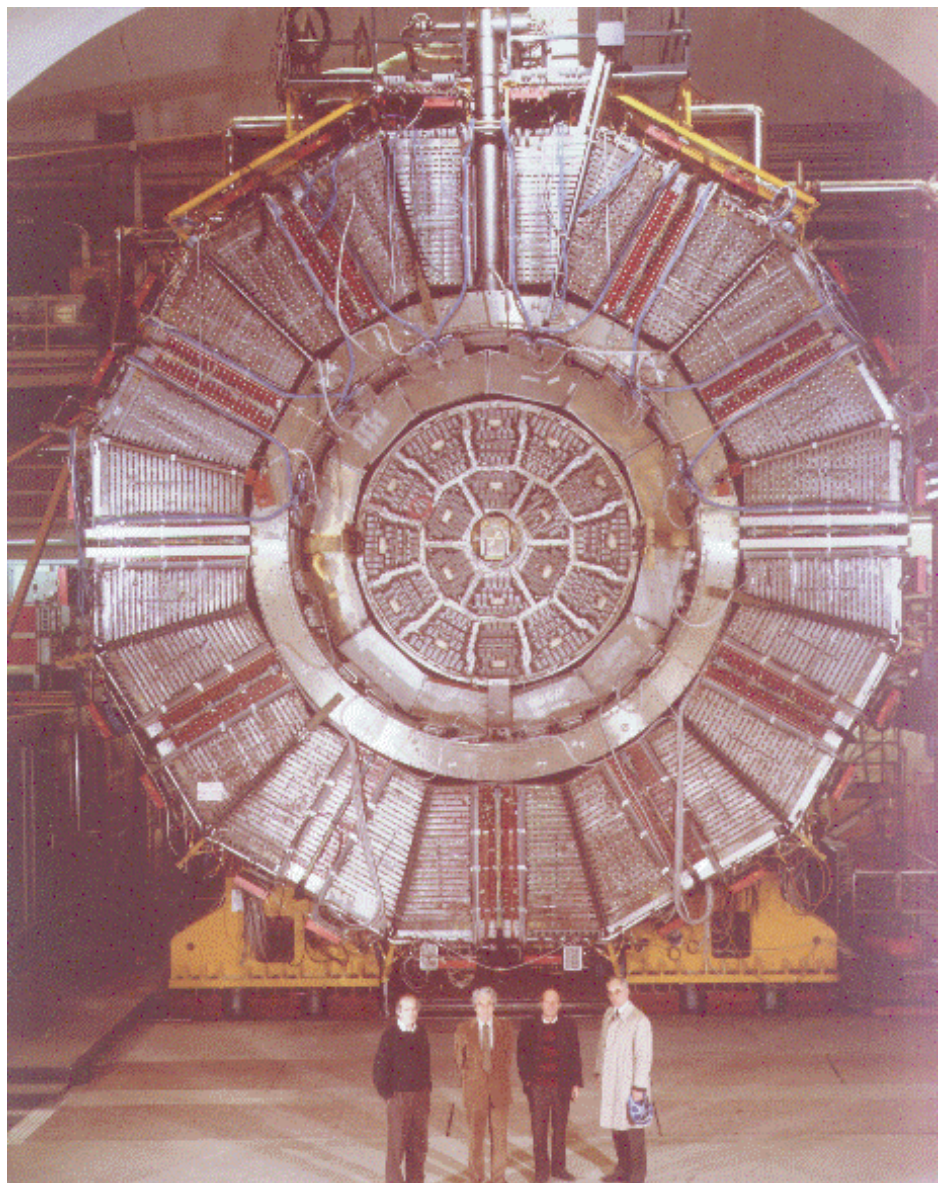


The ALEPH Detector used between 1989-2000 at LEP

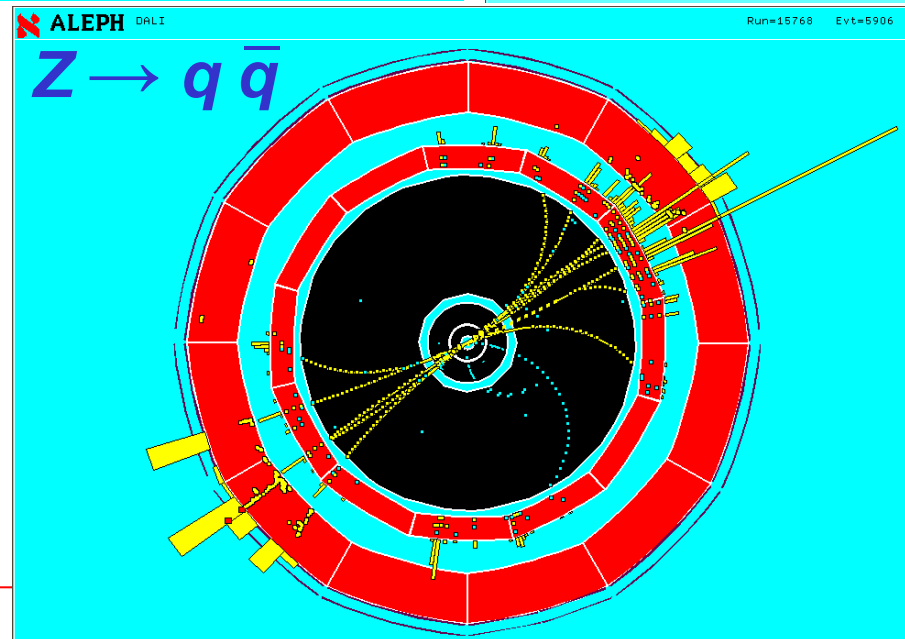
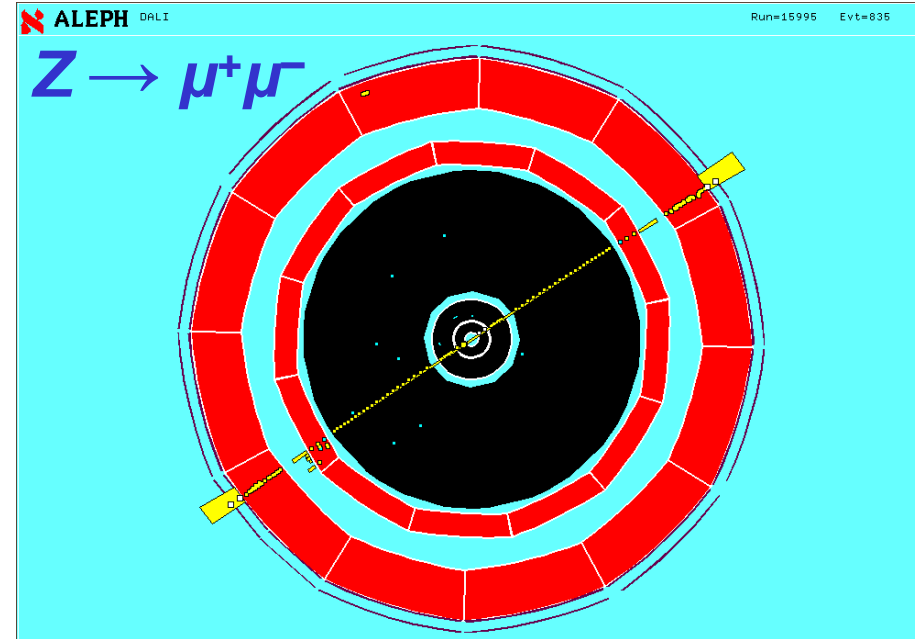
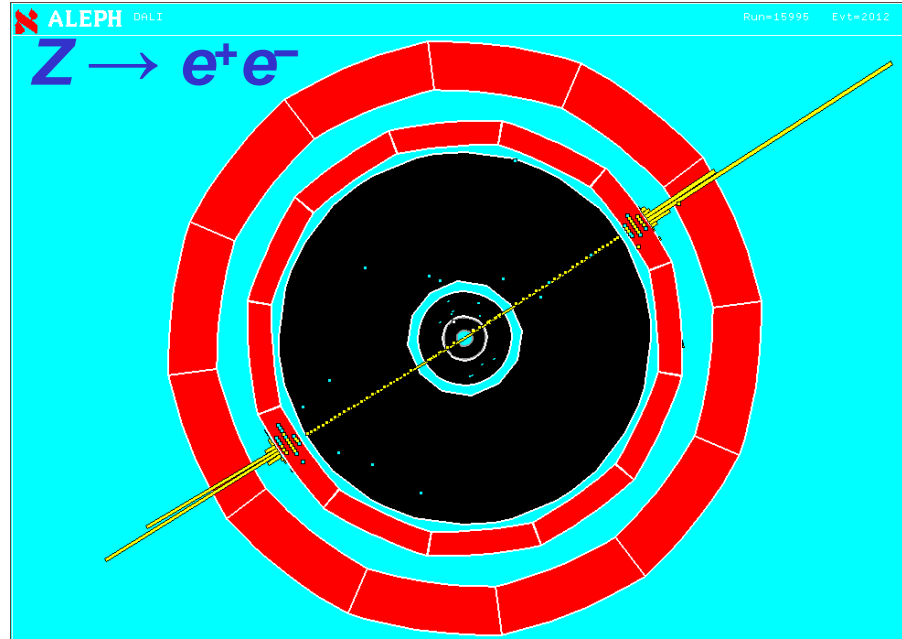


- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

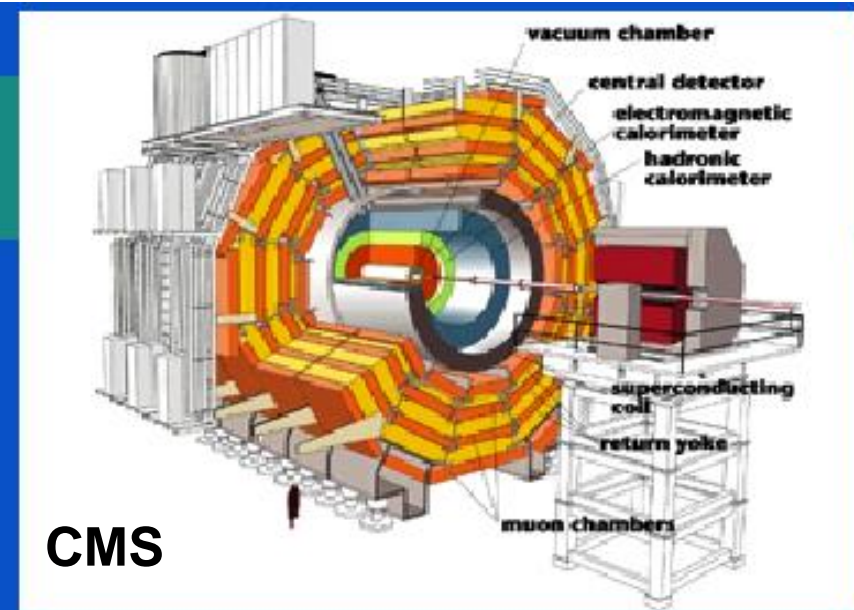
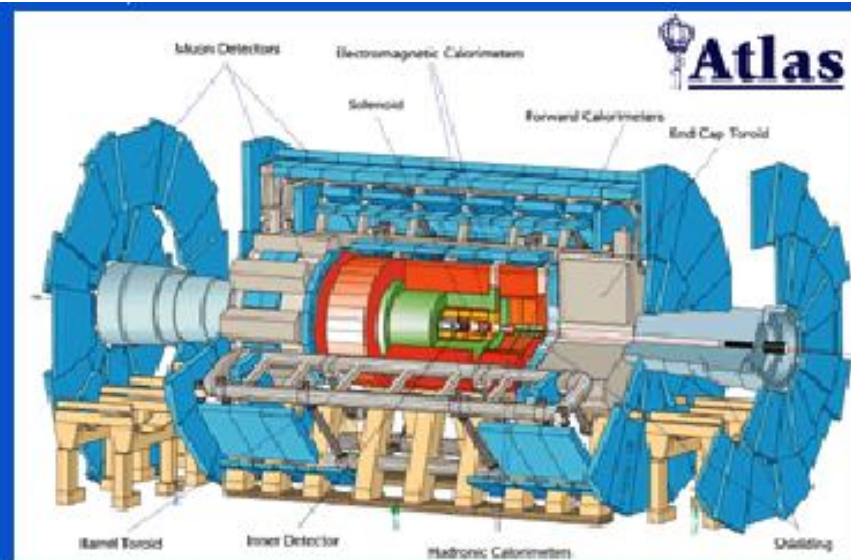
The ALEPH Detector



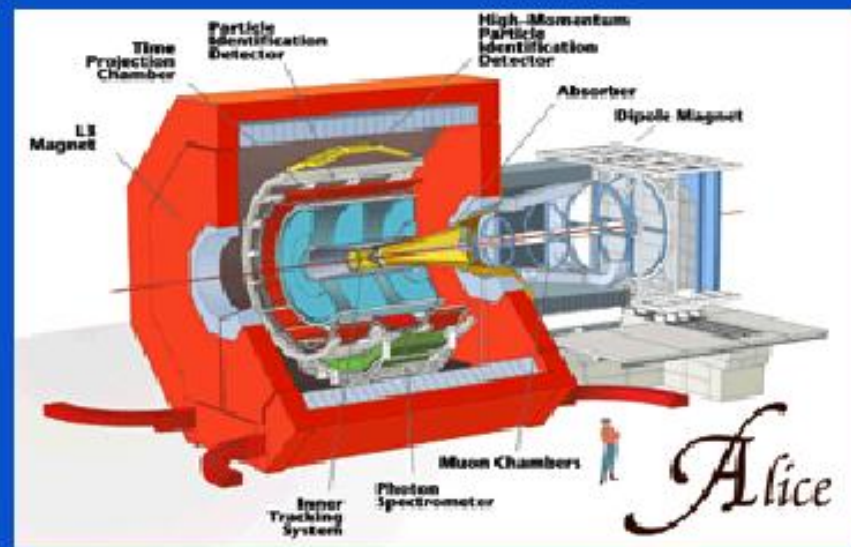
Some Recorded ALEPH Events



LHC Detectors

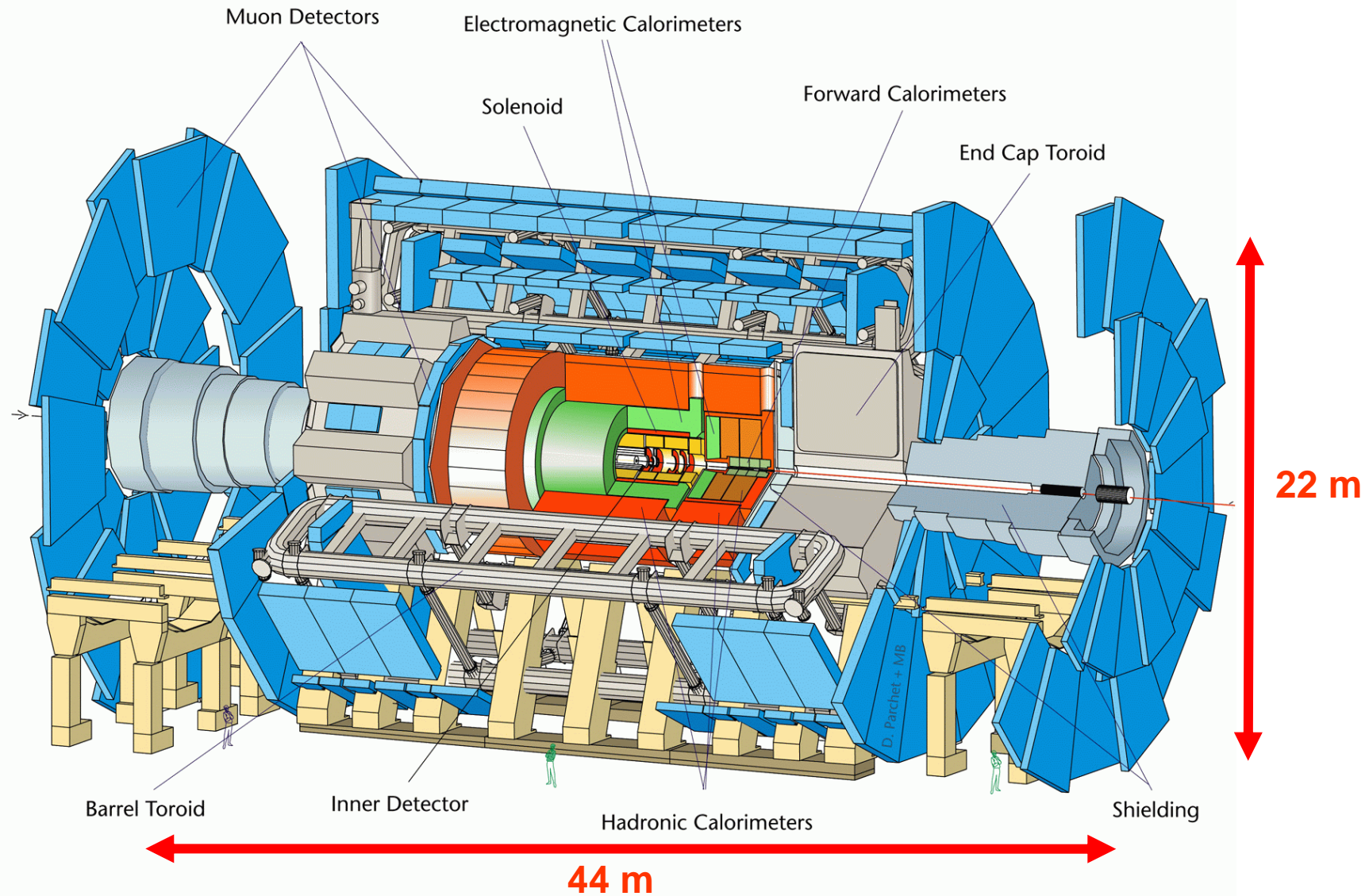


CMS



ATLAS Detector is a combination of sub-detectors

D712/mh-26/06/97



Four Main Parts of ATLAS

- **Inner tracker**

Measures the momentum of the charged particles

- **Calorimeter**

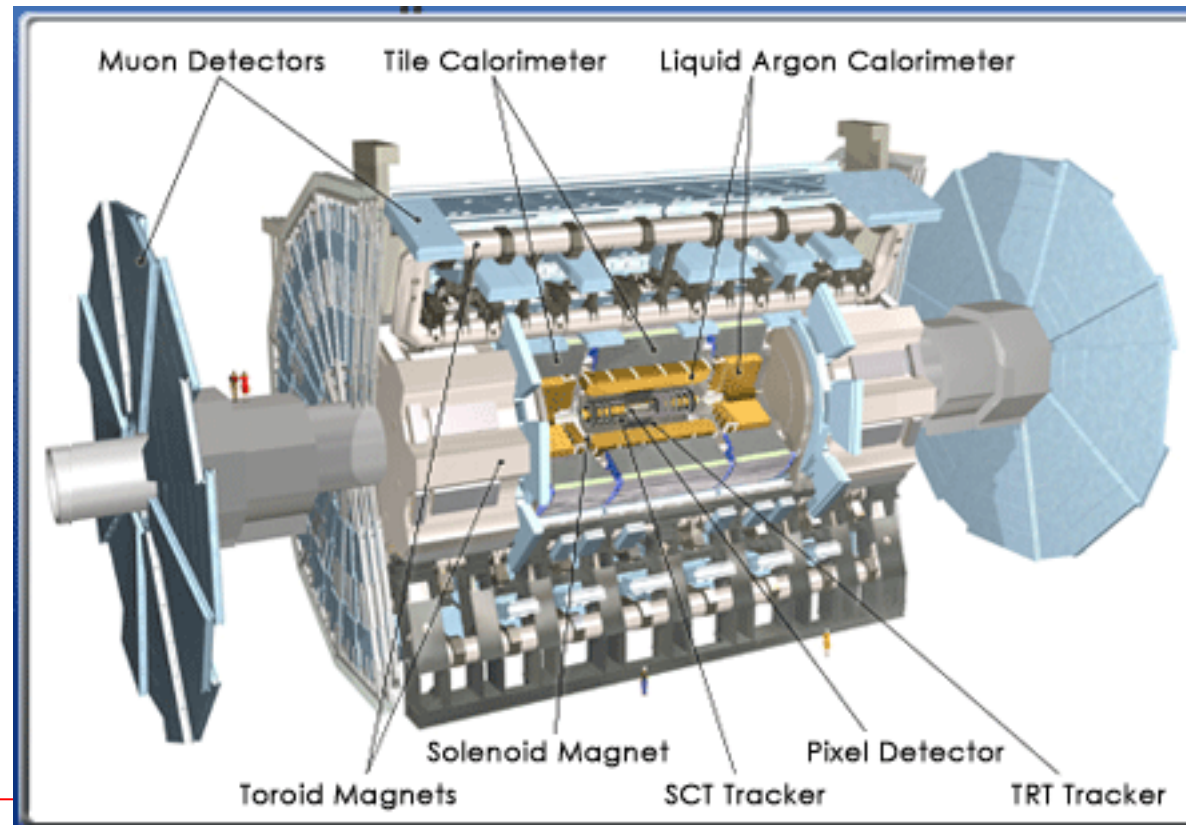
Measures the energies of particles

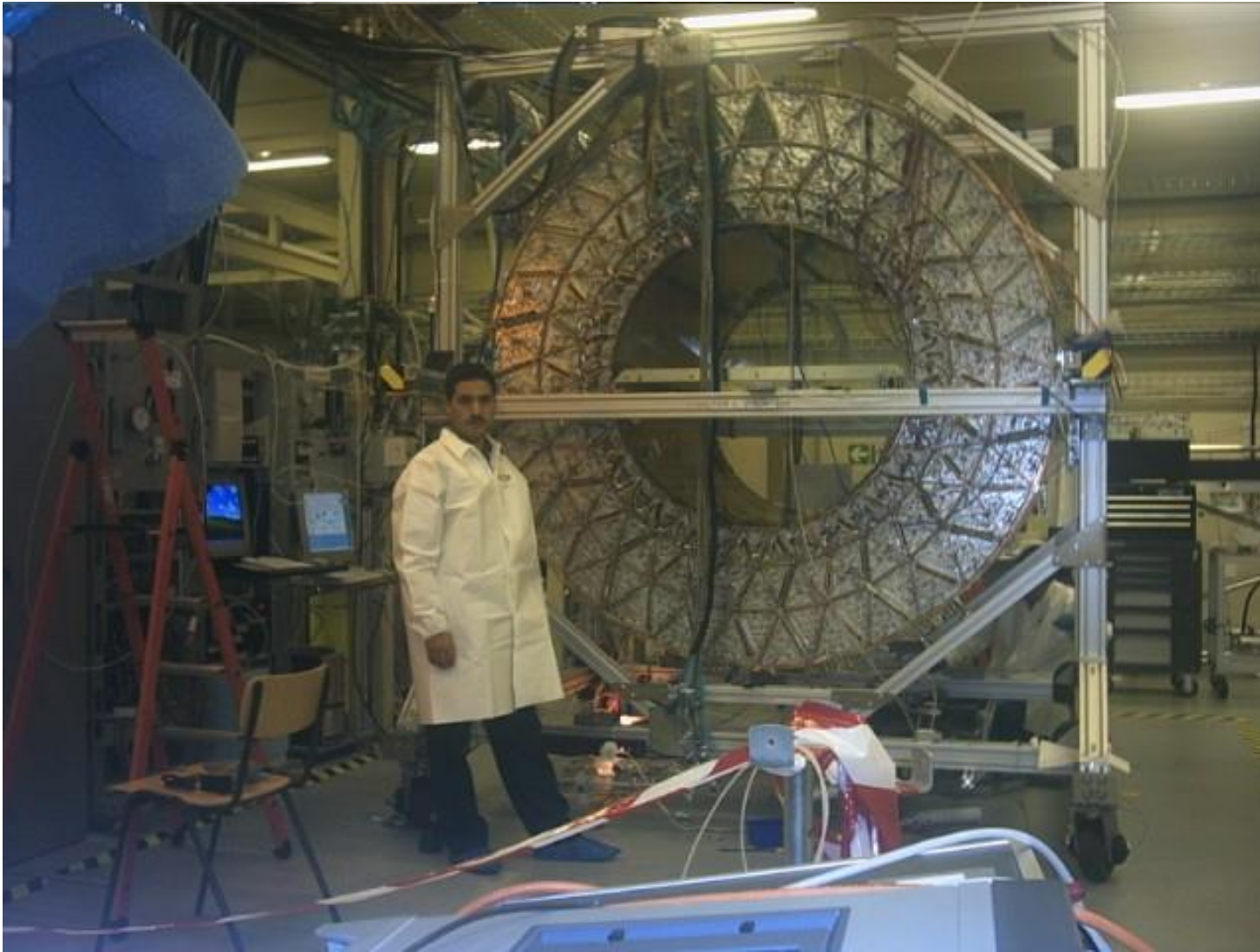
Muon Spectrometer

Measures the energy of muons

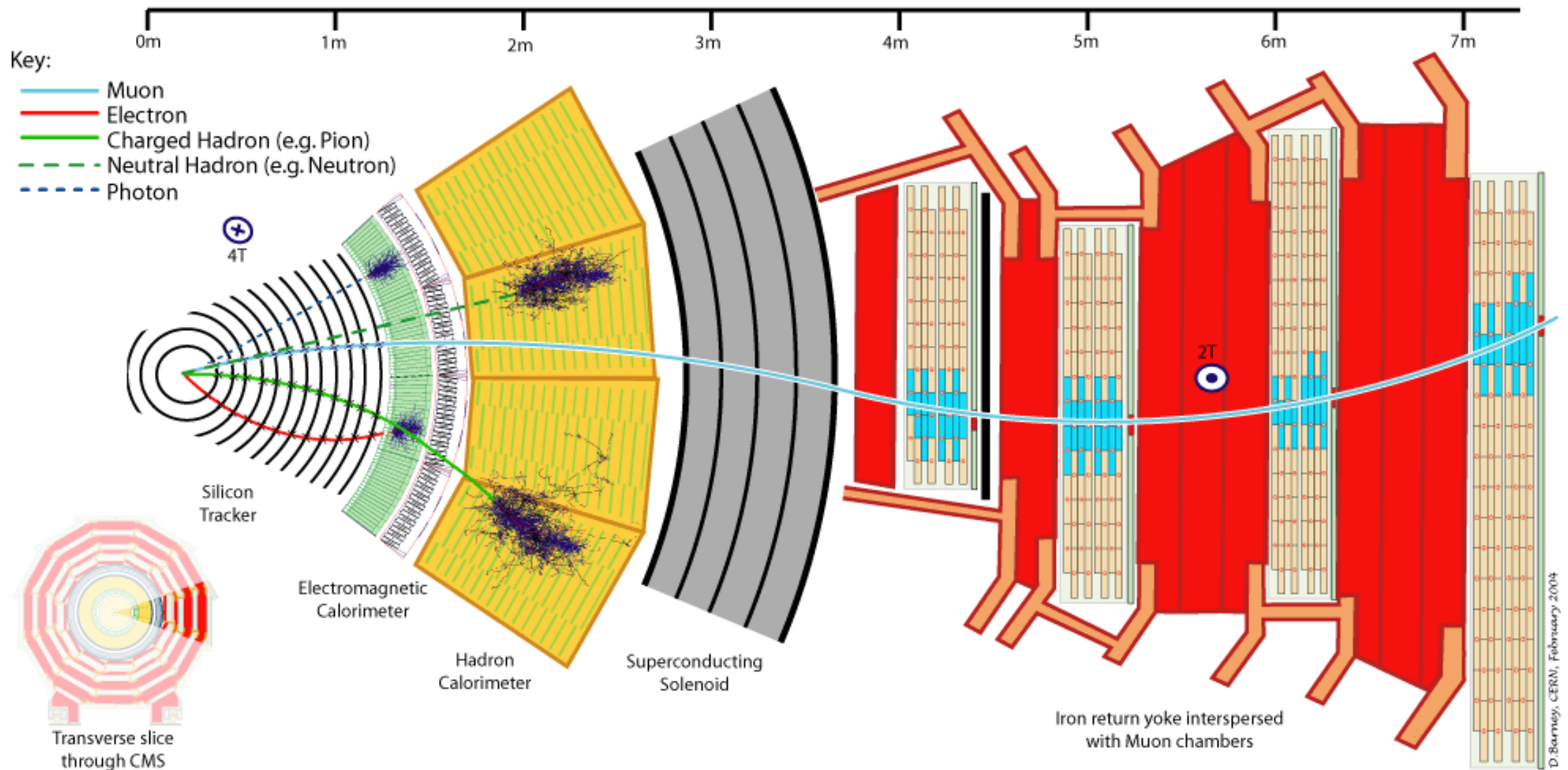
Magnet System

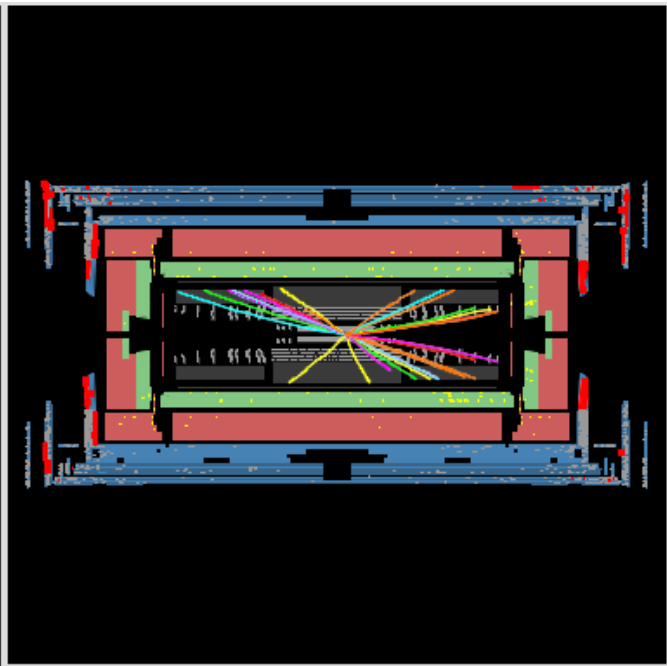
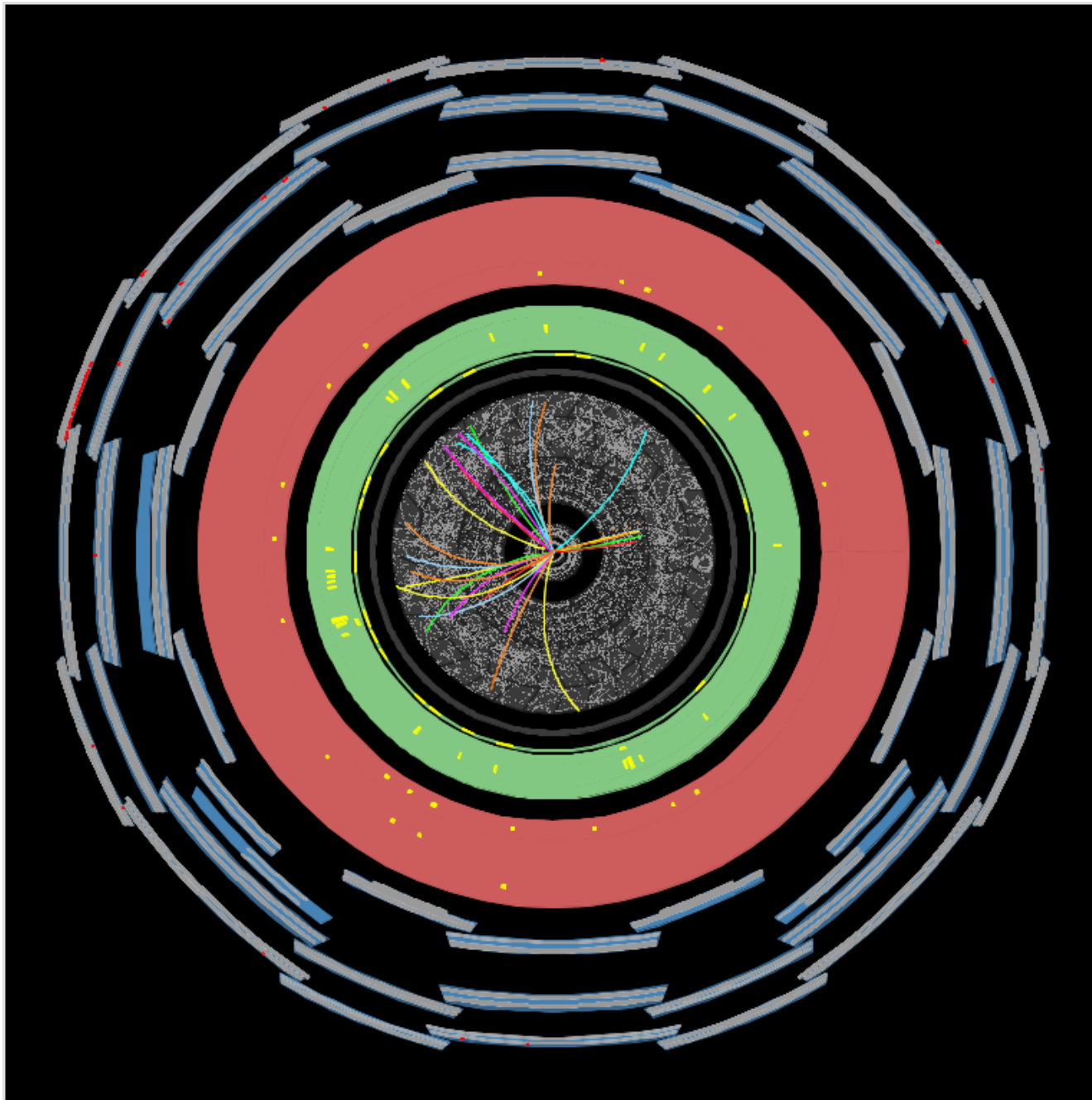
Supplies the magnetic field to bend the charged particles for measuring p.





CMS Detector is a combination of sub-detectors





ATLAS EXPERIMENT

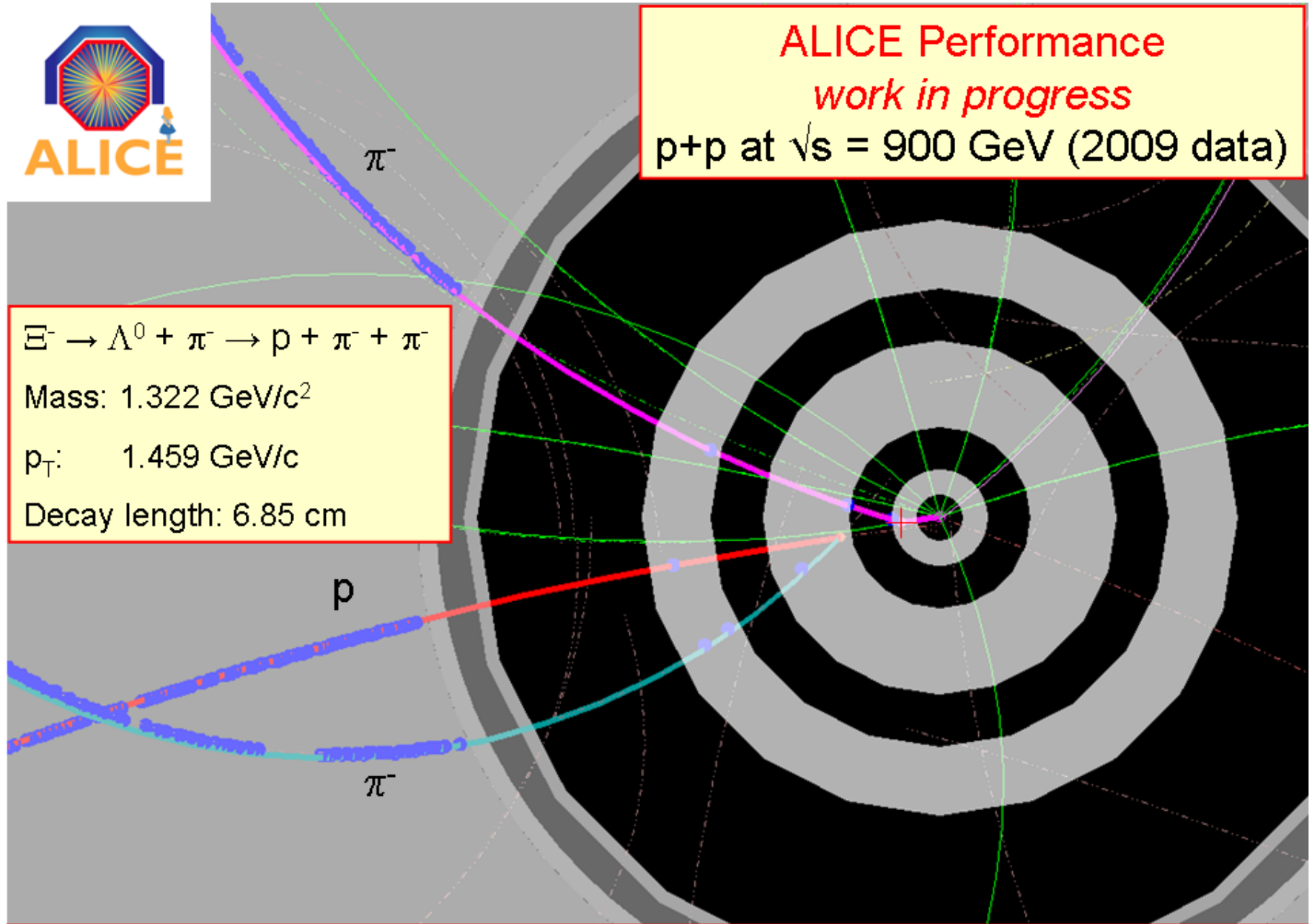
Run Number: 213486, Event Number: 215114913

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

Snapshot of a proton collision
directly from the ATLAS experiment



ALICE Performance
work in progress
p+p at $\sqrt{s} = 900$ GeV (2009 data)



$\Xi^- \rightarrow \Lambda^0 + \pi^- \rightarrow p + \pi^- + \pi^-$
Mass: 1.322 GeV/c²
 p_T : 1.459 GeV/c
Decay length: 6.85 cm

Run 104892, raw data chunk 09000104892020.130, event in chunk 1840

Problems

1. In the Tevatron, protons are injected from a ring that uses conventional magnets into a final, superconducting ring with about 150 GeV. Then they gain roughly 1 MeV per orbit as they move around the final ring. (a) How many orbits does a proton have to make to gain the full energy of 1 TeV? (b) Given that the ring has a radius of 1 km, how far does the proton travel inside the ring and how long does this final acceleration take?

2. At the Tevatron, protons and antiprotons, orbiting in opposite directions around a circle of radius of 1 km, are used for the collision at the $E_{CM} = 1.96$ TeV. Calculate the radiated power and energy loss per turn for the antiprotons.

3. The LEP electron synchrotron has a rated energy about $E = 50 \text{ GeV}$ and a radius of $r = 4.3 \text{ km}$. Calculate the radiated power and energy loss per turn for the electrons.

4. (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.

5. 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.

6. Calculate the minimum flight path necessary to distinguish pions from kaons if they have momentum $3 \text{ GeV}/c$ and TOF can be measured with an accuracy of 200 ps .

7. The momentum of a particle is measured as $p = 2.0 \pm 0.1$ GeV. If the time to travel the distance $L = 6.0$ m in TOF detector, whose time resolution is $\Delta t = 10.0$ ps, is measured as $t = 20.05$ ns, determine the mass of and the mass resolution for this particle.