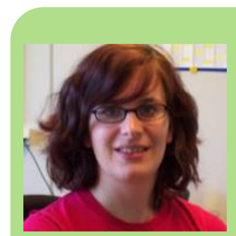
Detectors in Particle Physics: High-Resolution Cameras to See the Unseen



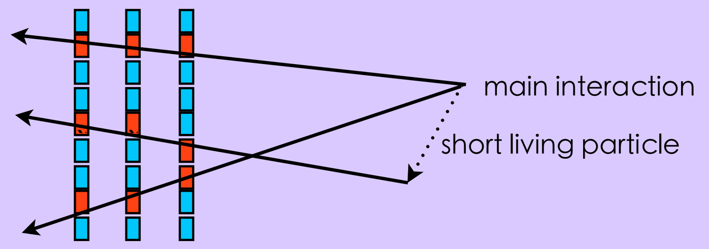
Anna Henrichs, Georg August University of Göttingen, Germany

65th Scottish Universities Summer School in Physics, August 2009

Tracking Detectors [1,2,5]

Purpose

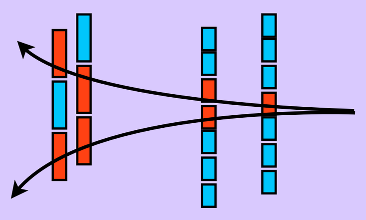
Measuring the exact spatial origin of a particle is one of the tasks of the tracking detectors. Particles originating from a short-living particle produced in a collision come from another vertex than the ones from the primary interaction.



If the tracking detector is located within a magnetic field the curvature of a particle 's trajectory allows to determine the charge and the transverse momentum of a particle - see Magnets.

Design

A typical inner detector consists of 2-3 different subsystems with increasing size and decreasing granularity.
Several detector layers are required to measure the trajectory and the momentum with a good lever arm.

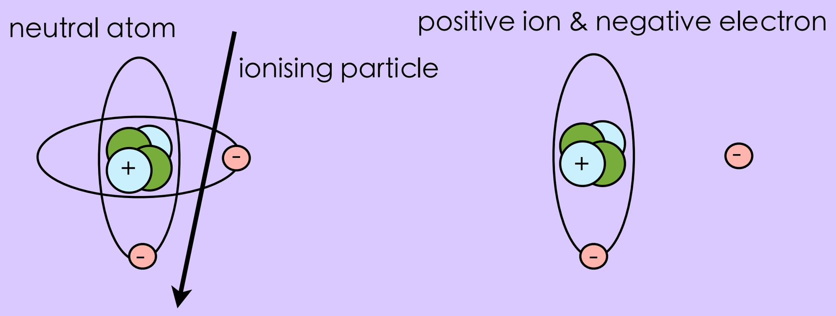


Closer to the interaction higher granularity is needed to distinguish tracks and find their origin.

The different layers are shifted to resolve ambiguities in track reconstruction and to cover the complete volume.

Ionisation

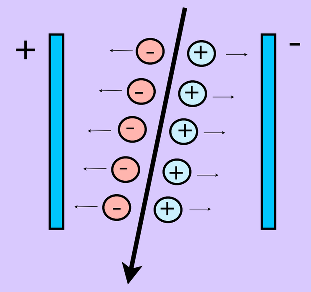
Ionisation is the physical process that all tracking detectors are based on. It describes the process of a particle causing electrons of the material to be separated from the rest of the atom.



The transferred energy from the incoming particle to the shell electron allows the electron to overcome the binding forces to the atomic core.
Neutral particles cannot be detected in the tracking detector as they do not interact with the shell electrons of the atoms.

Detection

The free electrons can be collected by applying a potential difference to the material and measuring the electric current.



By measuring the drift time for electrons between track and anode, the spatial resolution can get even smaller than the sensor size.

Traveling electrons can create a shower of additional electrons and increase the current.

Material

Particles should cross the detector leaving only the minimal ionisation energy without being stopped. Therefore, light material is needed for sensors and support structure.

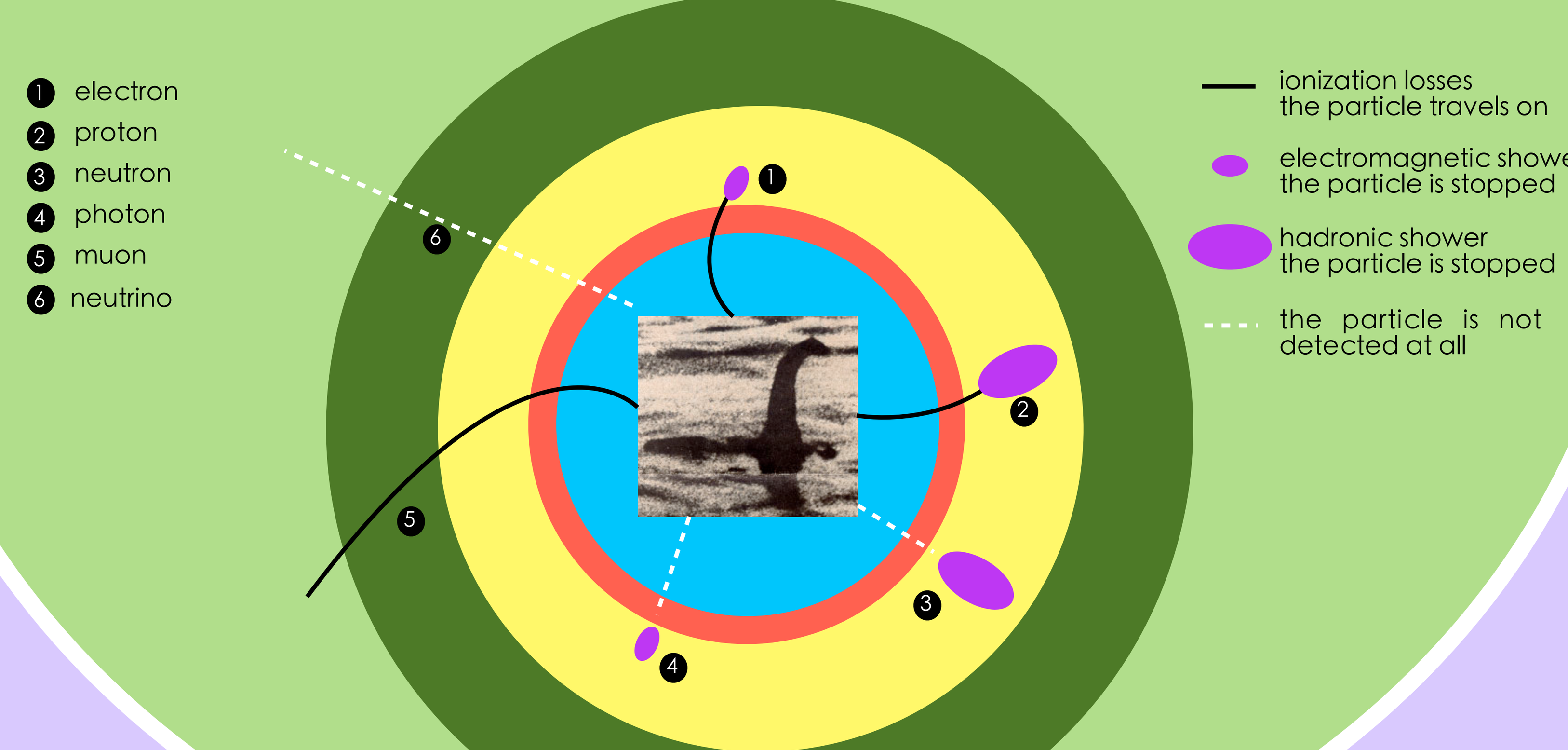
As main sensor material in most detectors silicon, a semiconductor, is used. Highly segmented sensors can be build using common technologies and a fast readout speed allows to measure the signal for each collision separately.

By applying a reverse voltage to the doped semiconductor, a depletion zone is created. Traversing particles ionise atoms in this zone and the free electrons travel towards the edges of the sensor.

A Classical Multipurpose Detector in Particle Physics

Different particles interact with different parts of the detector. By combining information from all subsystems, particle physicists are able to distinguish and identify the different types of particles. Looking at the particles coming from the collision in the center of the detector, physicists can study the nature of (new) short living particles that are created in these collisions.

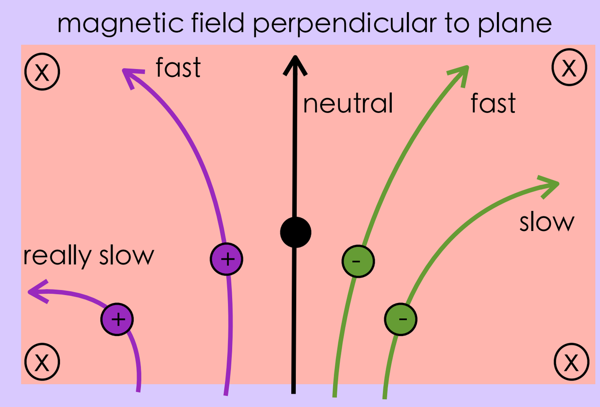
These detectors need to cover the complete volume around the interaction point to make sure that no particle, except for those that cannot be detected, can escape unseen. Modern particle detectors reach volumes of up to 40x20 metres and consist of several million readout channels.



Magnets

Why Magnets?

Charged particles are deflected in a magnetic field.



The curvature of a particles track is proportional to its velocity and momentum. The direction of the curvature shows the charge of the particle.

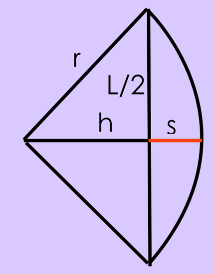
Momentum Measurement

For a known magnetic field B the radius r of a reconstructed track can be measured. This directly translates into the transverse momentum of the particle p_T

$$p_T[\mathrm{GeV}/c] = 0.3 \cdot B[\mathrm{T}] \cdot r[\mathrm{m}]$$

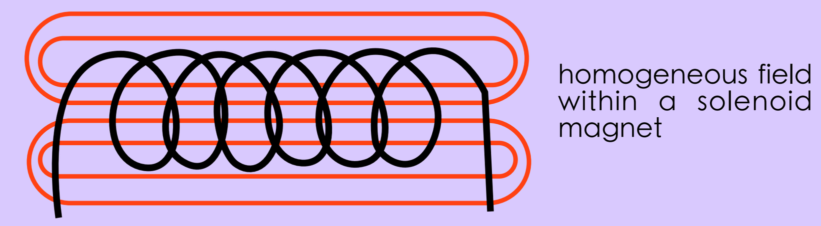
What is mostly measured is the sagitta of the trajectory using at least three spacepoints.

$$r = \frac{L^2}{8s}$$



Location of Magnets

The transverse momentum of charged particles is measured in the inner tracking detector. For a precise measurement a homogeneous magnetic field in the tracking detector is needed.
Therefore the magnet system is surrounding the inner detector.



An additional magnetic field in the muon system allows a precise measurement of the muon momentum. The only detector with a second magnet system is the ATLAS experiment[2] at CERN.

Types of Magnets

Two different types of magnet systems are used:

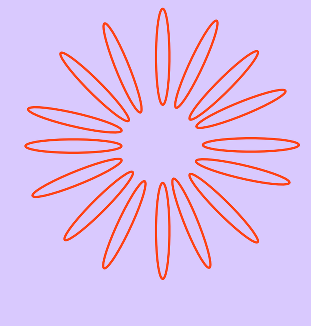
Solenoids

Solenoid magnets are loops of wires around the detector system. When an electric current passes through the, a very homogeneous magnetic field is created inside.

This type of magnet is typically used in particle physics detectors. For the CMS[3] detector the return yoke is creating an additional field within the muon system.

Toroids

A toroid magnet consists of several separated loops along the detector 's length.



The magnet surrounding the muon system in the ATLAS experiment is a toroid.

References

[1] Detectors for Particle Detection, K. Kleinknecht, Cambridge University Press, ISBN 0521648548

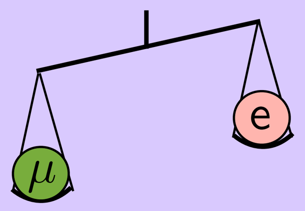
[2] The ATLAS Experiment at the CERN Large Hadron Collider, The ATLAS Collaboration, G. Aad et al, 2008, JINST 3 S08003

[3] The CMS Experiment at the CERN LHC, The CMS Experiment, S. Chatrchyan et al, 2008, JINST 3 S08004

Muon Detectors [5]

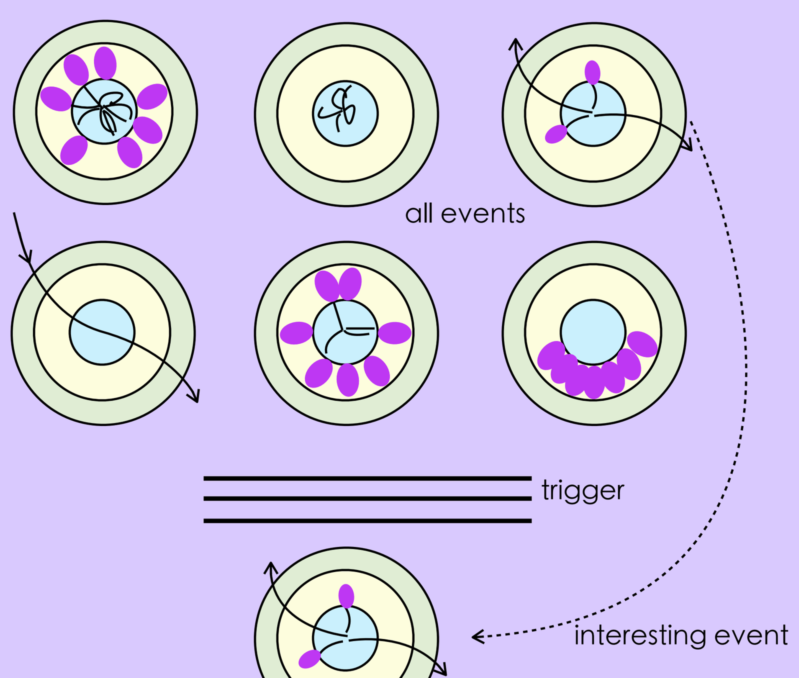
Purpose

Muons are heavier versions of electrons. They leave tracks in the inner detector, but cannot be stopped by the calorimeters.



The purposes of the muon detectors are identifying a muon very fast and measuring its trajectory and momentum precisely, especially within a magnetic field.

Fast identification is needed for triggering - the reduction of stored data size by choosing only interesting events.
The muon detectors are used as fast readout is possible and muons often hint at interesting physics.



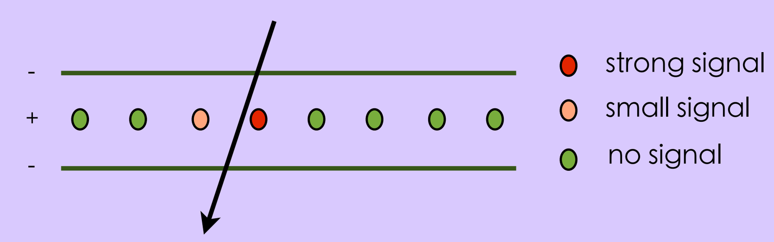
Detector Types

As the muons are charged, minimum ionising particles, the detection is always based on the ionisation of material. The physics is the same as for the inner tracking detectors, but the muon system needs to cover an extremely big volume.

Different types of muon detectors are used:

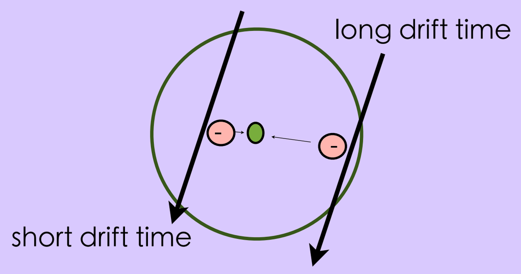
Wire Chamber

Wire chambers are areas filled with gas and anode wires in the center. Passing muons produce free electrons that are collected at the wires.



Drift tubes

The drift time of the free electrons to the anode wire in the center of the tube is used to measure the exact trajectory of the muon.



A signal to start the measurement needs to be provided by another detector.

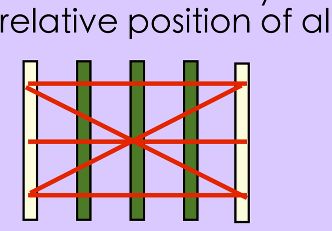
Scintillators

A scintillator is a material emitting light when an energetic particle passes through. This is one possible detector for fast triggering.

Alignment

The larger the detector, the more difficult it is to align all parts within a few μm. This is needed to measure trajectories with high spatial resolution.

The position of the different subdetector parts can be monitored by an optical system, measuring the relative position of all parts.



Optical sensors are attached to all layers and reference frames.

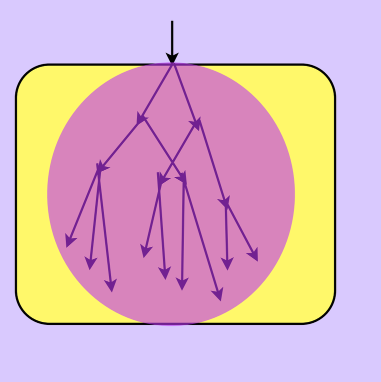
In addition, tracks from cosmic muons can be used even before first collisions take place to study the positions of the different detector layers.

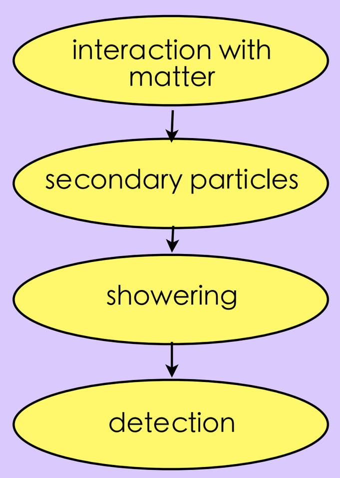
The final alignment is then done using tracks from collision and correcting displacements in reconstruction

Calorimeters [1,2,3,4]

General Concept

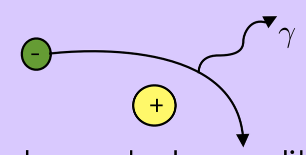
Calorimeters are detectors to measure the energy of a particle based on a four-step process occuring when particles cross material:



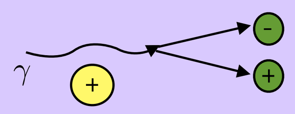


Interaction With Material

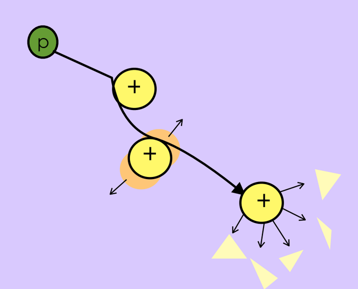
Electrons interact by emitting Bremsstrahlung. The electron changes direction after it is attracted by the positive charge of the nucleus. The emitted particle is a photon.



Near a nucleus, photons split into pairs of electrons and positrons.



Hadrons, like protons, are scattered by nuclei, excite nuclei and can even crash into nuclei and destroy them.

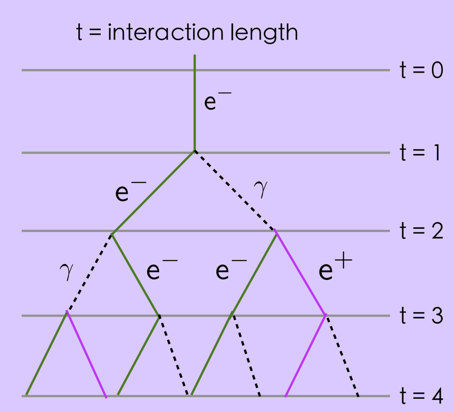


Electromagnetic Showers

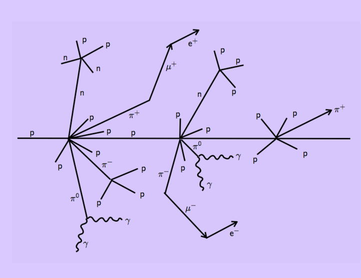
When electrons, positrons and photons hit material they convert into each other immediately.

Showering continues until particles get too slow to produce new particles.

Energy of primary particle
$\propto$
Number of particles in shower



Hadronic Showers



Hadronic showers have a fast maximum, a long tail and consist of all kinds of particles.
The more compact the material, the shorter the shower.

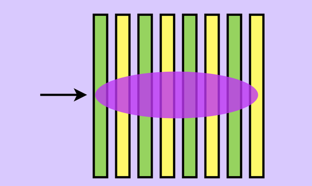
Detection

Showers from electrons and photons end earlier than the ones from hadrons. This allows the division into the inner electromagnetic calorimeter, where all showers occur, and the outer hadronic calorimeter, that is only reached by hadronic showers.
The optimal material and setup can be chosen for each separately.

Two concepts:

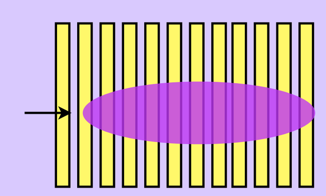
Sandwich Calorimeter - alternating active detector material and passive absorber material.

+ cheaper
+ optimal choice of material
- not all energy is detected



Homogeneous Calorimeter - all detector material is active.

+ fast readout
+ high energy resolution
- expensive
- bigger



Active material is either liquid or gas with potential difference collecting ionisation electrons or scintillating material collecting photons.
Passive material can be lead, plastic, copper, etc.