Detecting Particles and Reconstructing Events

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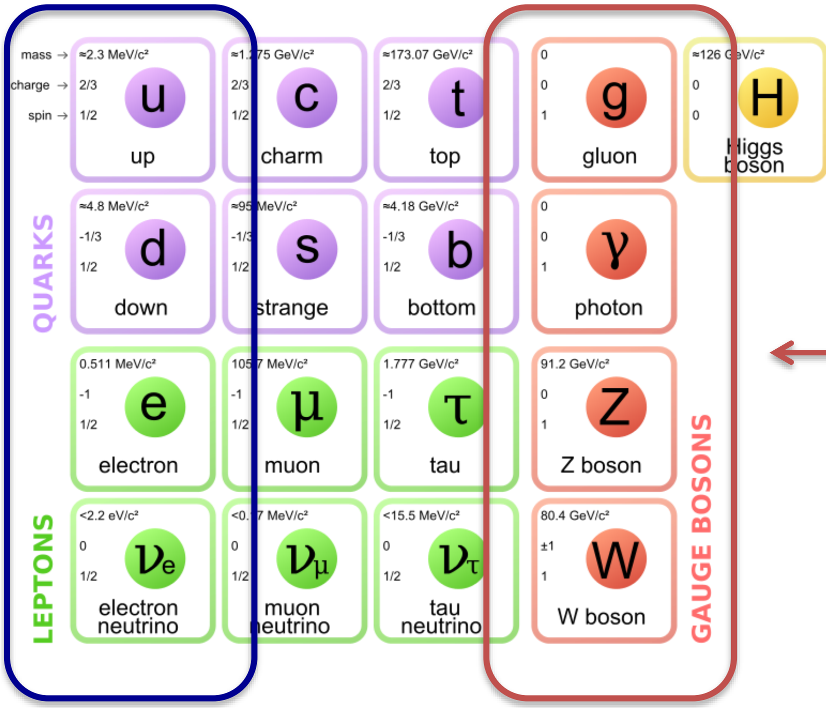
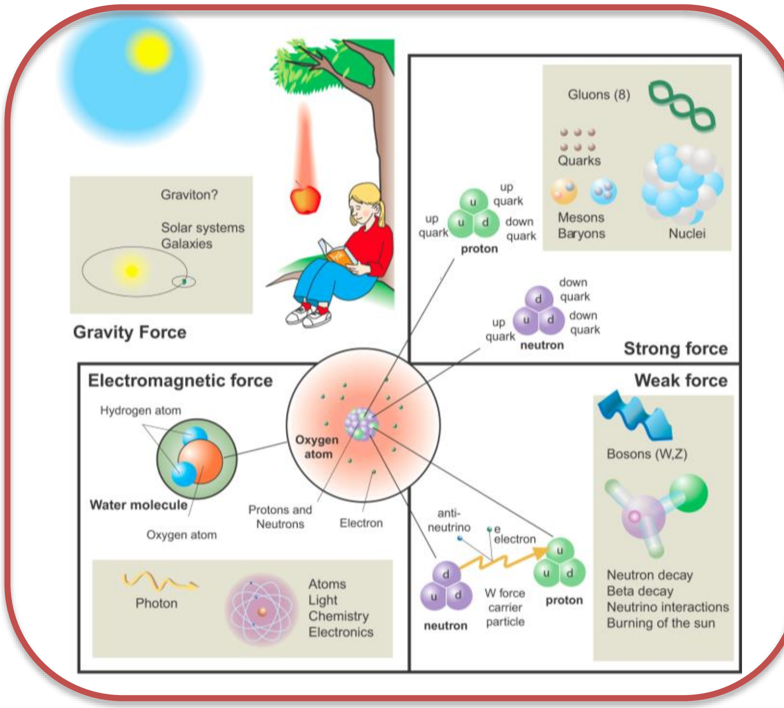
with inputs by K. Shaw, S. Shrestha, J. Stelzer

What we Learned Already

Standard model: Elementary particles and forces





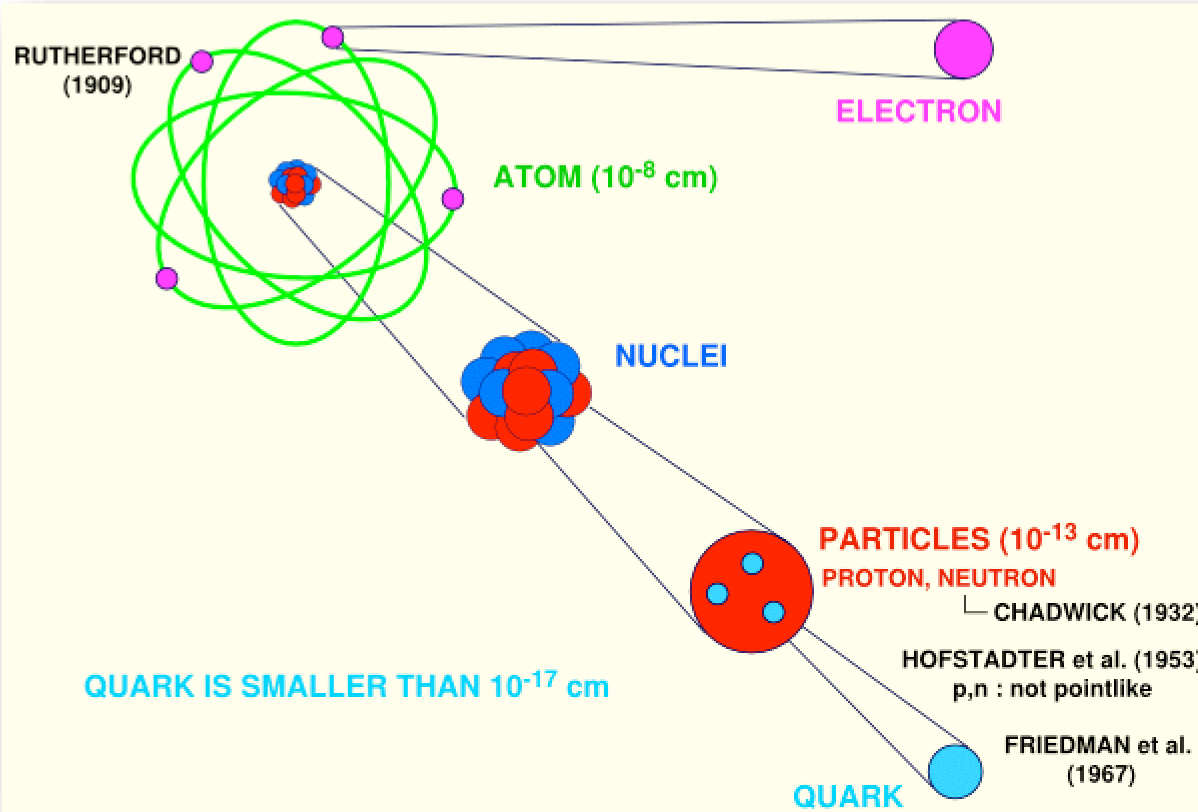
First family is what we are made of

4 forces govern our life

And the newly found Higgs to give us mass !

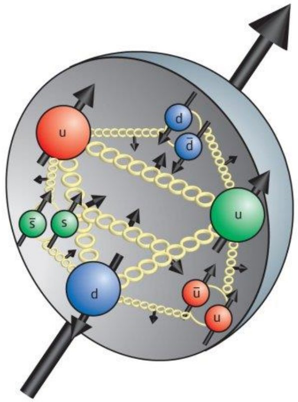
We all Heard about Accelerators

Particle beams to understand the structure of matter



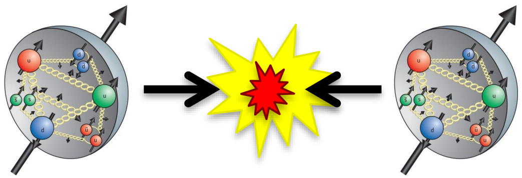
… starting with Rutherford in 1909

Production of New Particles



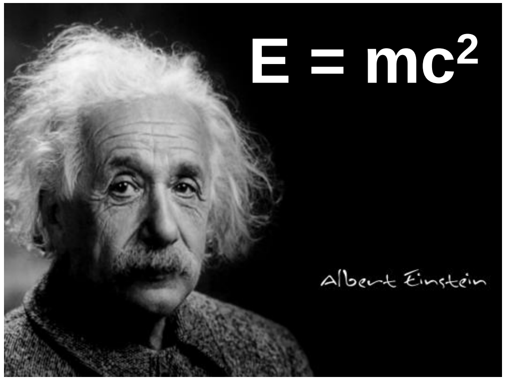
3 quarks form a proton : 2 u + 1 d

… and a whole sea of quarks, anti-quarks and gluons – all bound by strong force



Many possible interactions between the components of two colliding protons.

Many ways to create particles

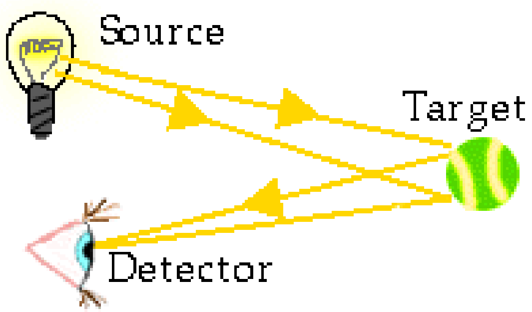


+ law about conservation of energy

$M_{\text{New Particle}} < E_1 + E_2$

How we Observe Small Things

Light is reflected of everything (visible) in our environment and detected by our eyes



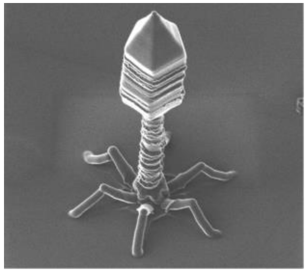
5 mm

For smaller things we invented the microscope.

Higher resolution with smaller wavelength

10 um

Optical microscope



200 nm

Electron microscope

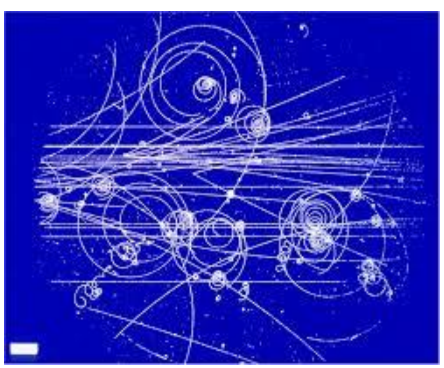
Observing Particles

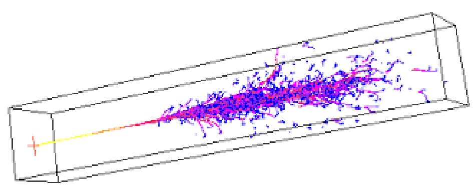
Can we build a super microscope ?

Not really: particles too small, too fast, too many !

Different principle: look for traces of the particle when it goes through material

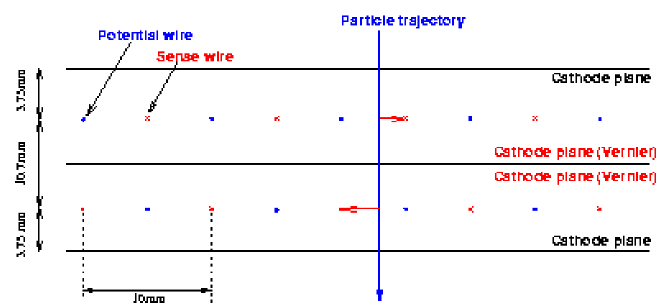
Charged particle through superheated fluid





Scintillating material

Charged particle through an ionizing gas



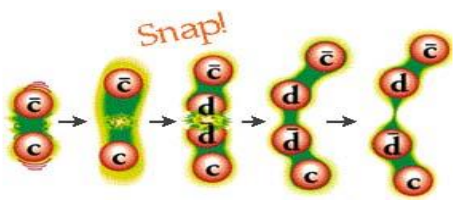
Which Particles can we Detect?

Particles with long lifetime

Electrons, muons, protons, photons, neutrinos, kaons, pions, neutrons

Can be observed

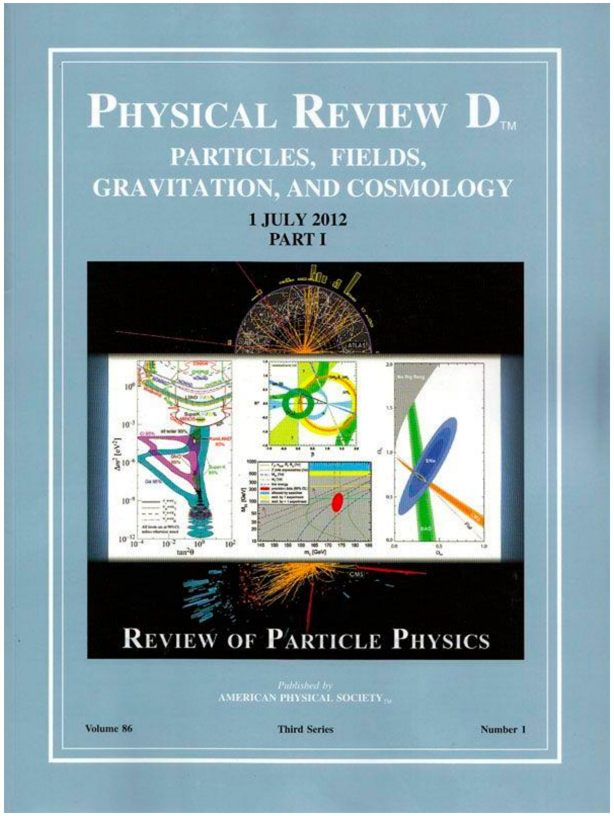
Quarks hadronize into jets



Can be observed

Short-lived particles

Can not be observed



Particle Data Group: sorts and publishes all the knowledge we collect in HEP

Building a Detector

What do we want to discover ? Which theory do we want to prove?

- Atomic structure (1909), structure of the proton (1967), top quark (1995), the CP violation (2001), the Higgs particle (2012)

What particles can we detect? Which technologies do I have?

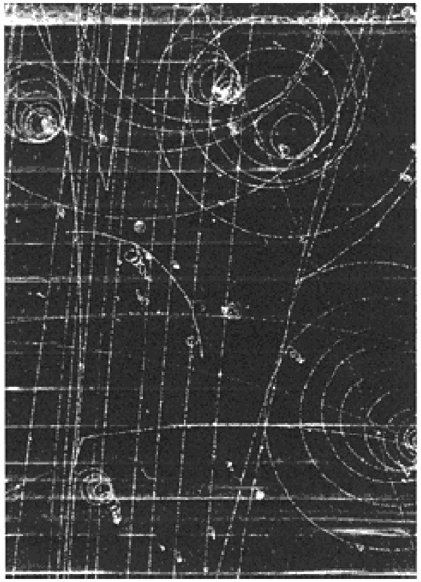
- Basic Detector designs are often similar. Always newest technologies

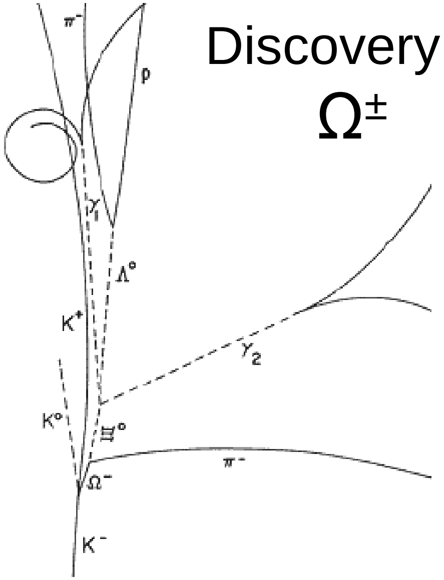
Early Detectors

Gargamelle

Bubble chambers (50's – mid 80's)

Particles through superheated liquid produce bubbles → stereo photographs





Discovery of $\Omega^{\pm}$

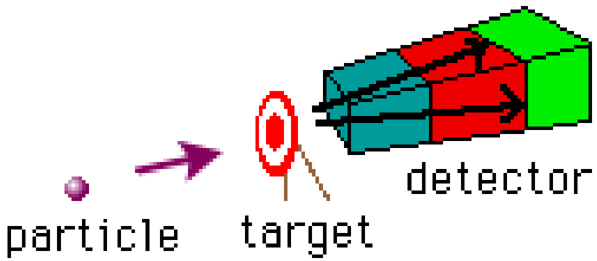
Big European Bubble Chamber

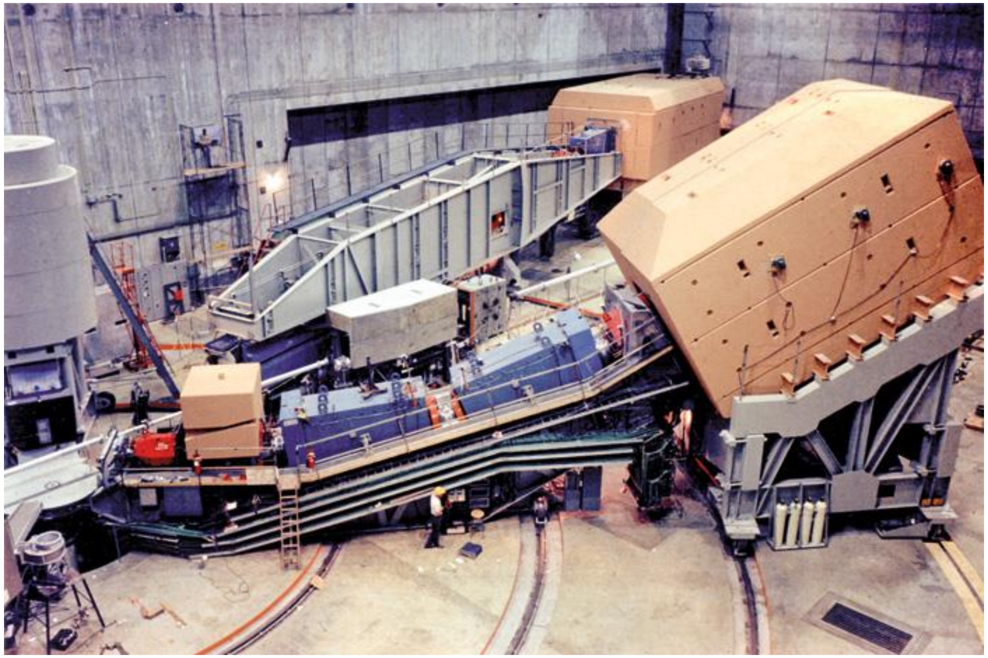
Important principle: charged particle tracks in a magnetic field to measure momentum and mass.

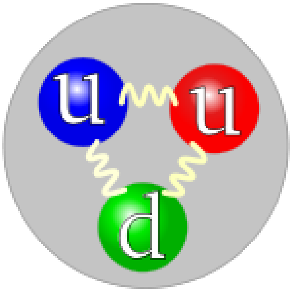
Many ideas and techniques born then are still valid

Fixed Target Detectors

Beam on fixed target → detector on the other side of target



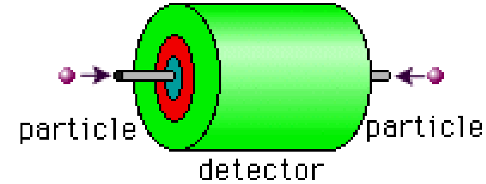


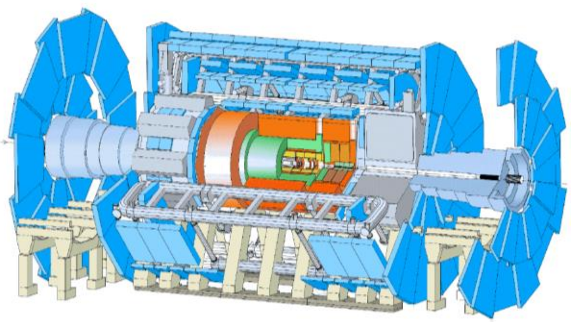


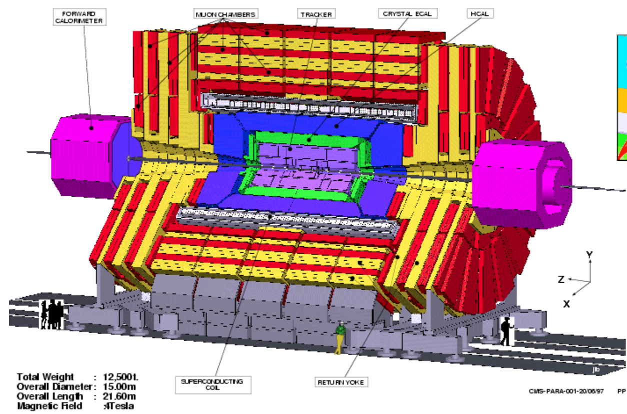
SLAC Endstation A: discovery of the quark structure (1967)

Colliding Beam Detectors

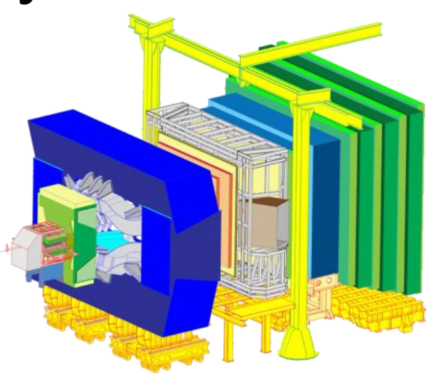
Detectors usually surround symmetrically the interaction point



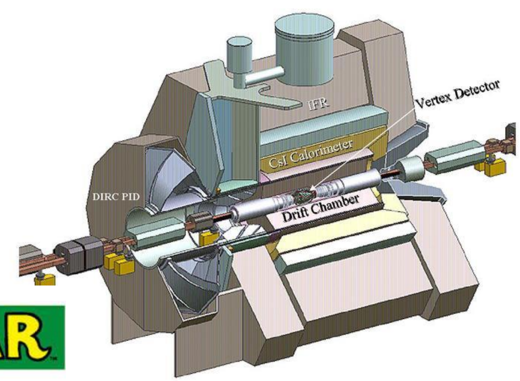




But not always…

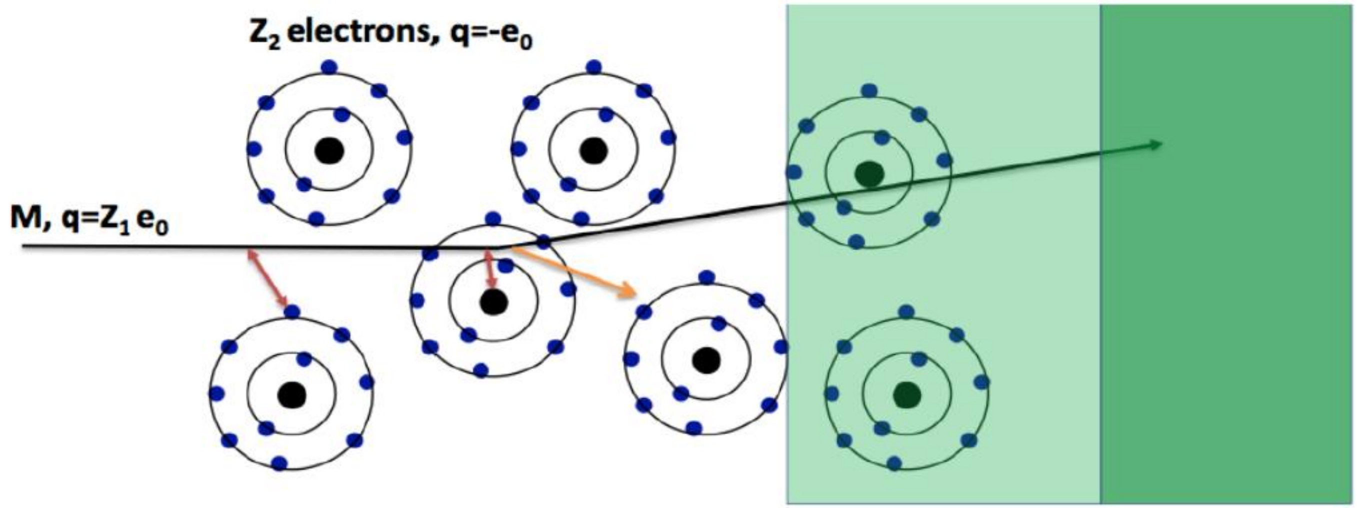


Physics happens in a small region



Asymmetric beams

How Particle interaction with matter?



Interaction with the atomic electrons.
The incoming particle loses energy and the atoms are **exited** or **ionised**.

Interaction with the atomic nucleus.
The incoming particle is deflected causing **multiple scattering** of the particle in the material.
During this scattering a **Bremsstrahlung 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 **Cherenkov radiation.** When the particle crosses the boundary between two media, there is a probability of 1% to produce an Xray photon called **Transition radiation.**

e^-/e^+ interaction with matter

1. Ionization:

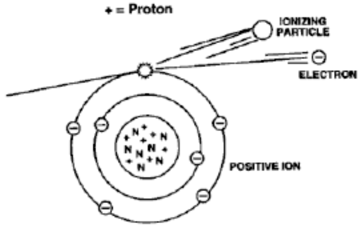
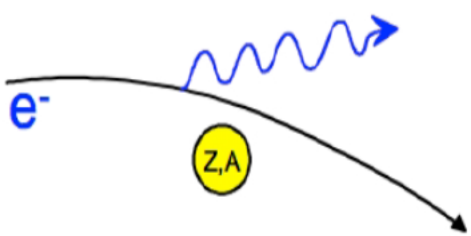
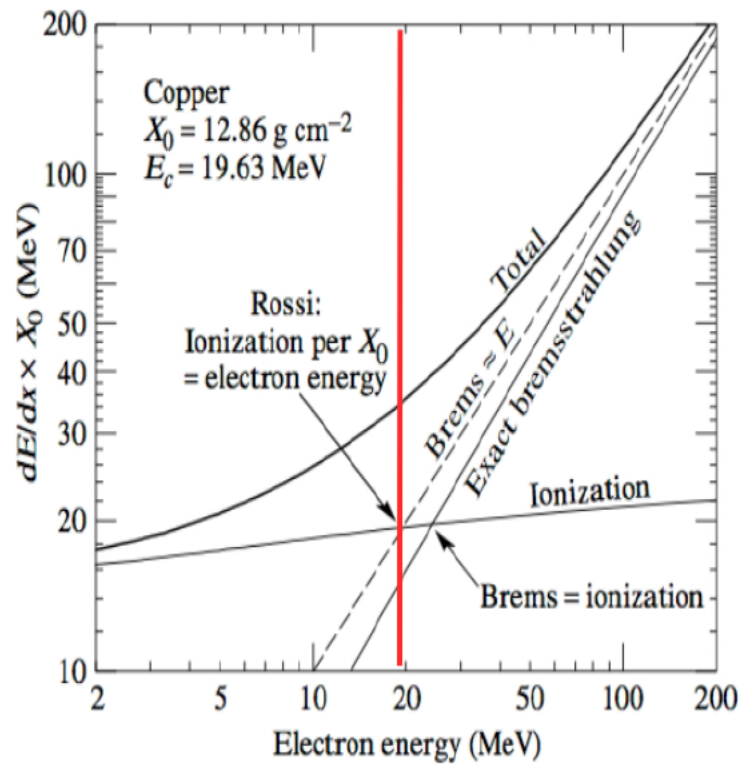


Figure 2-XIII. Electron Removal by Ionization

2. Bremsstrahlung

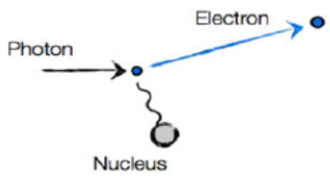


- Energy lost depends on energy:



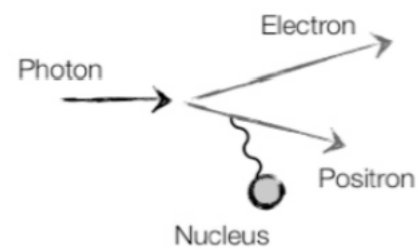
γ interaction with matter

1. Photoelectric

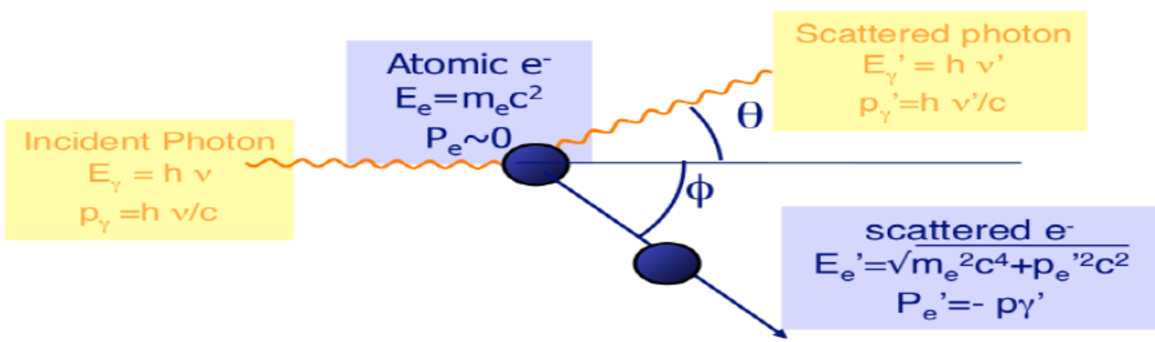


γ + atom $\rightarrow$ e^- + atom$^+$

3. Pair production:

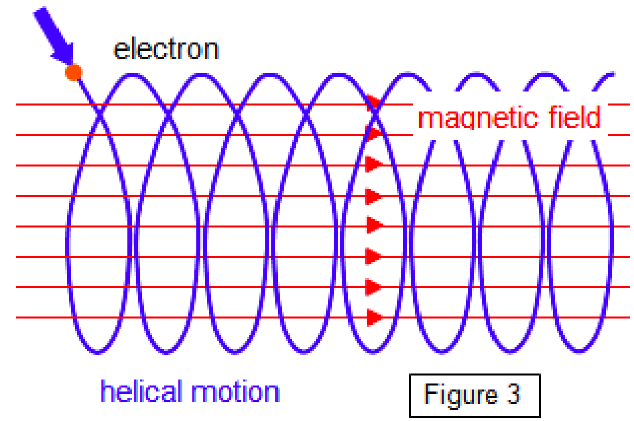


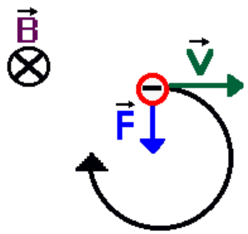
2. Compton Scattering



Measuring Momenta : Tracking

Lorentz Force bends charged particles when moving through a magnetic field *B*

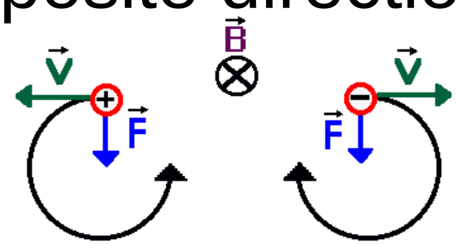




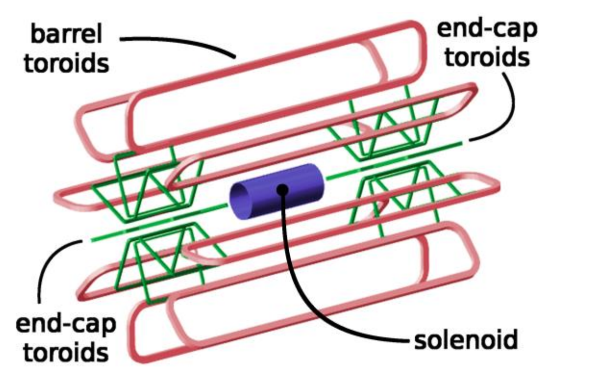
$$\boxed{\vec{F}_L = q\vec{v} \times \vec{B}}$$

Determine transverse momentum $\boxed{p_T = Bqr}$

Opposite charge bend in opposite direction



ATLAS has three magnet systems

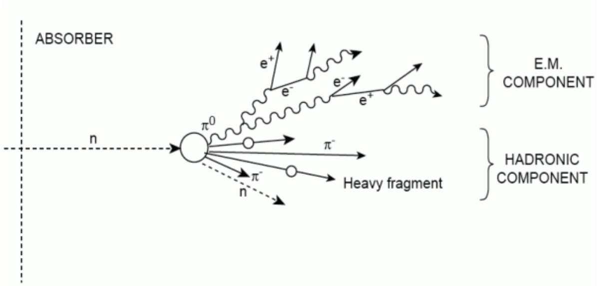


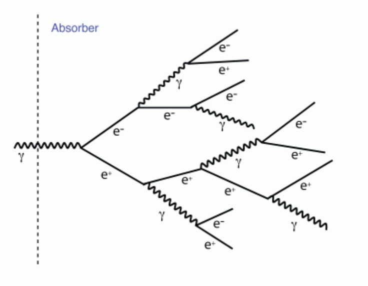
Measuring Energy : Calorimetry

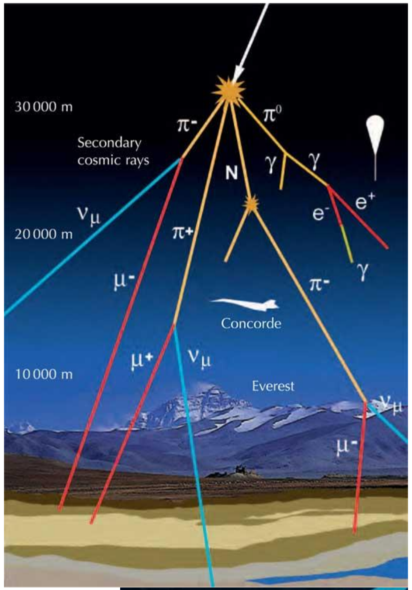
Calorie: old French energy unit (Latin: calor=heat)

A calorimeter consists of:

- Dense material to <u>fully absorb</u> the particle
- Active material to produce an output signal ~ E

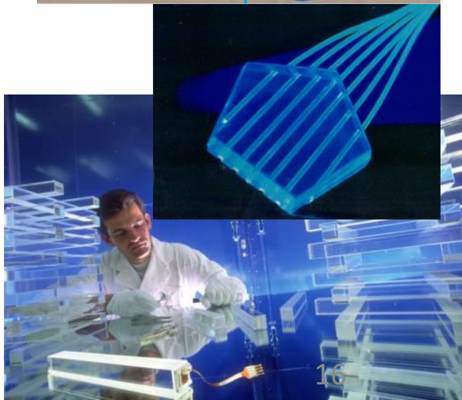






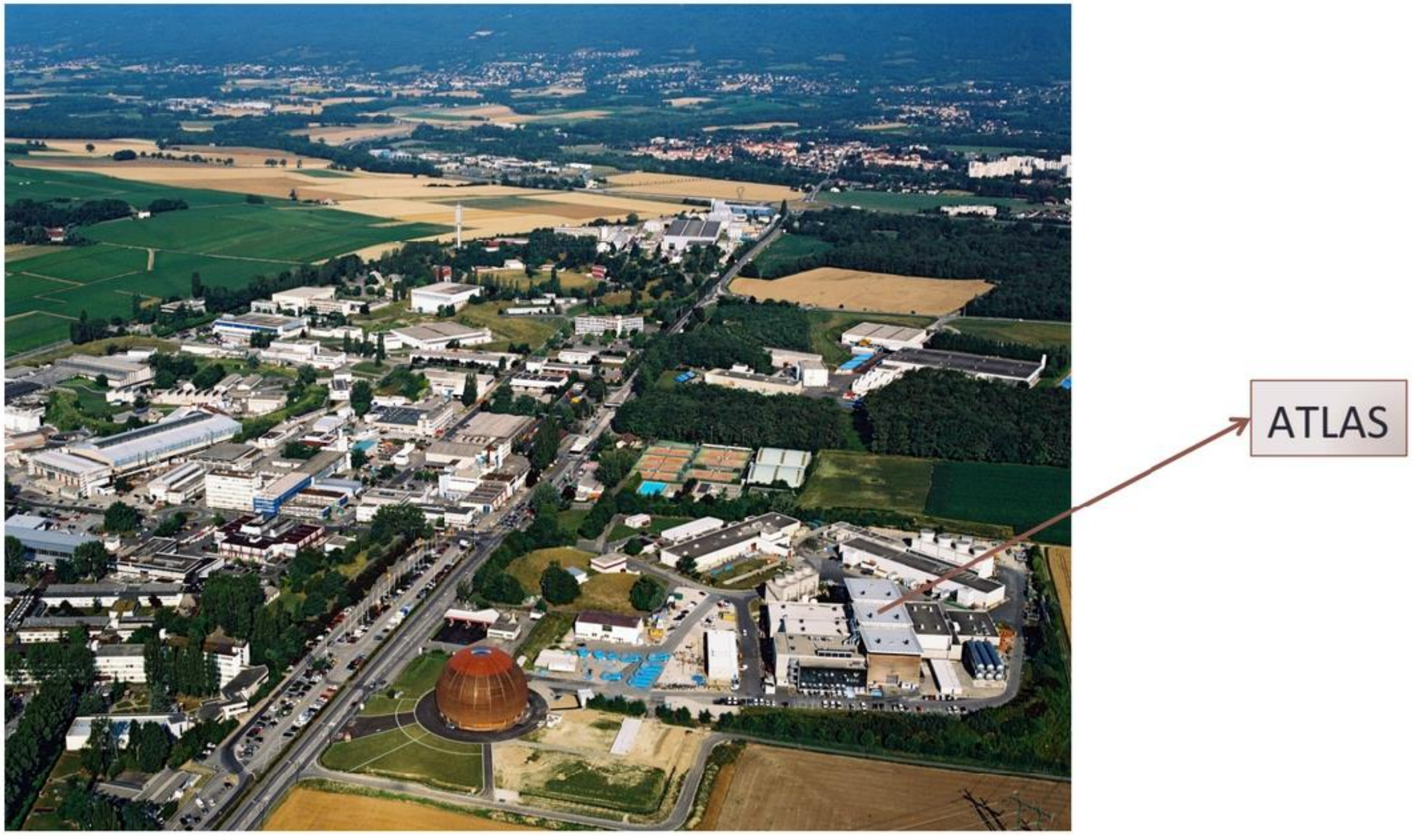
Absorber and active materials

- The same → homogeneous calorimeter
- Different → sampling calorimeter
- Two slides, detail of showering, invasive procedu



ATLAS

CERN Map

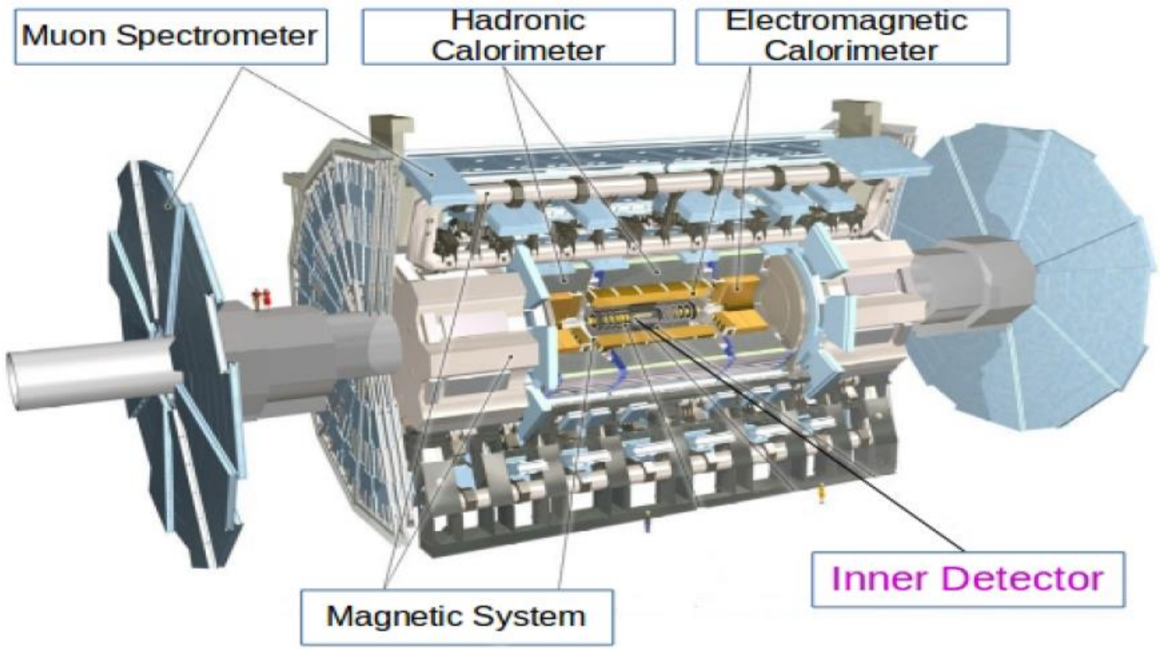


The Large Hadron Collider (LHC)

- Largest particle accelerator.
- 27 km circumstance
- 100 m underground
- Four main experiments.
- Collide two proton beam with center of mass energy 13 Tev.

ATLAS: A Toroidal Lhc Apparatus

- General purpose detector, 44 m long, 25 m hight & weight about 7000 tons.



Different Designs, same Principle

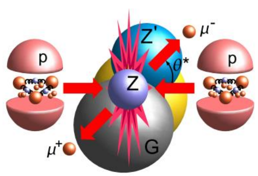
Flight direction

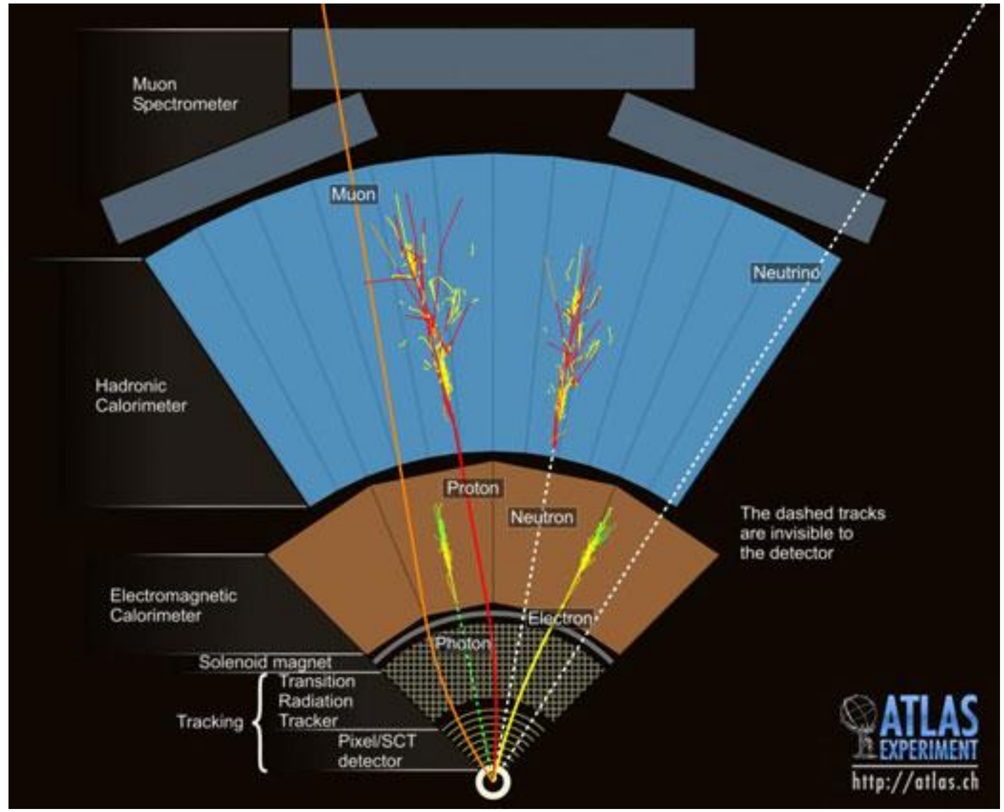
Muon System
(magnetic field)

Hadronic
Calorimeter

Electromagnetic
Calorimeter

Tracking
(magnetic field)

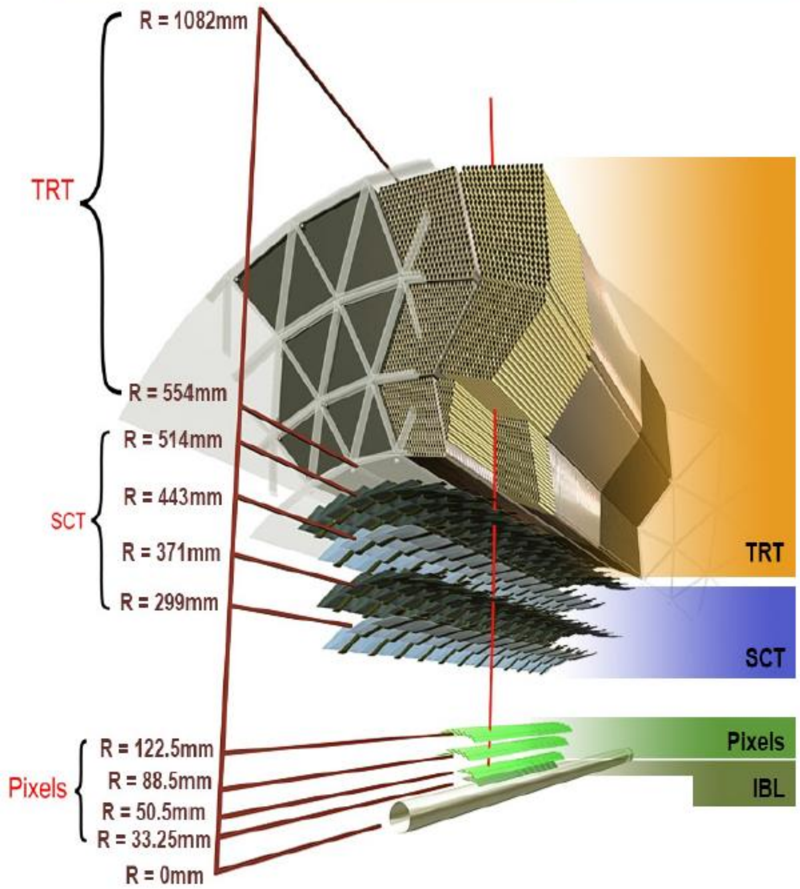




Different particles have different properties and leave different signatures → allows the identification of particles

Which stable particle is leaving no trace ?

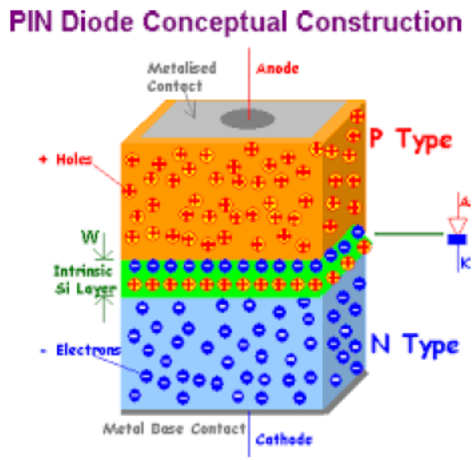
ATLAS components 1: Inner Detector

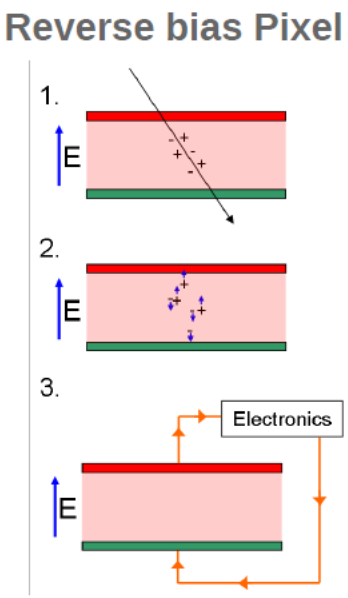


- Inner most detector
- Silicon based detector.
- Dedicated to high precision tracking (momentum measurement) of charged particle.
- composed of three subsystems: TRT, SCT and Pixel detectors.

What is pixel?

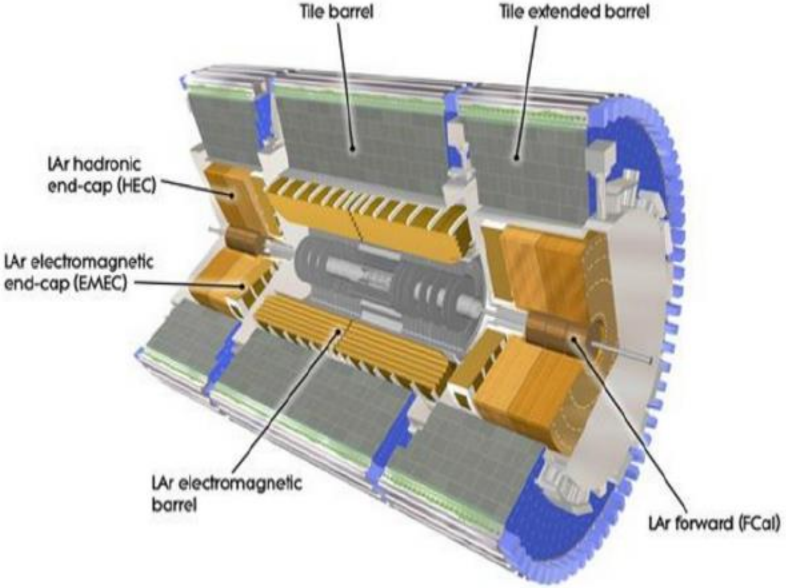
Pixel simply two pn junction stacked to each other.

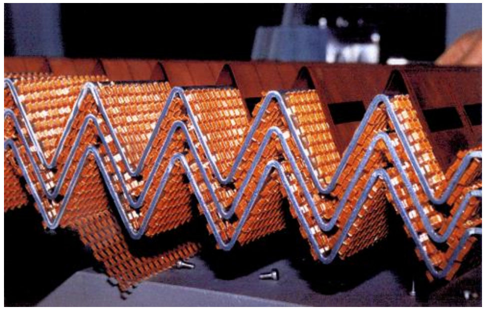


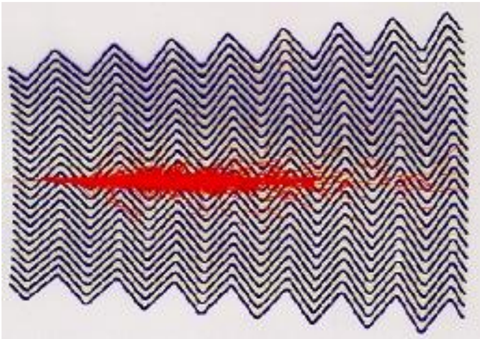


- Once a particle passes through deposits enough energy to create **electron-hole pairs**. Charges drift under the effect of the electric field.

ATLAS components 2: Calorimeters



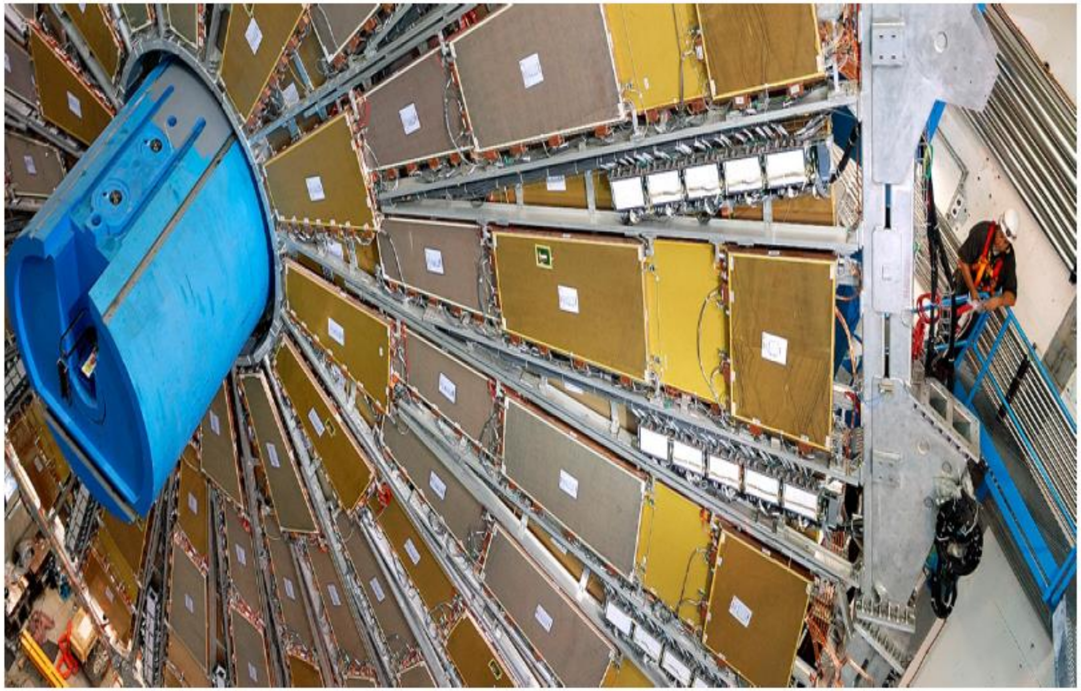


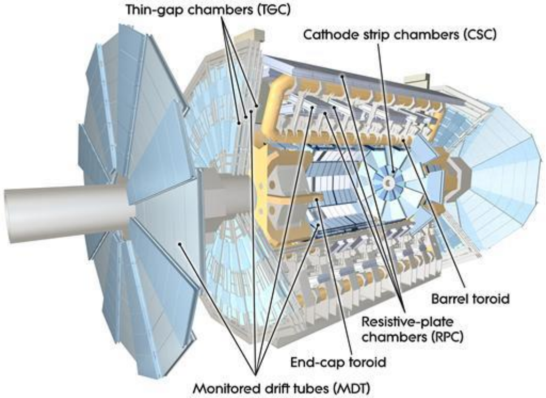


- measure energy loss of particle as it passes through the detector.
- Electromagnetic calorimeter (EM) measure the energy of electrons and photons as they interact with matter.
- Hadronic calorimeter sample the energy of hadrons (particles that contain quarks, such as protons and neutrons) as they interact with atomic nuclei.
- Calorimeters can stop most known particles except muons and neutrinos.

ATLAS components 3: Muon Spectrometer

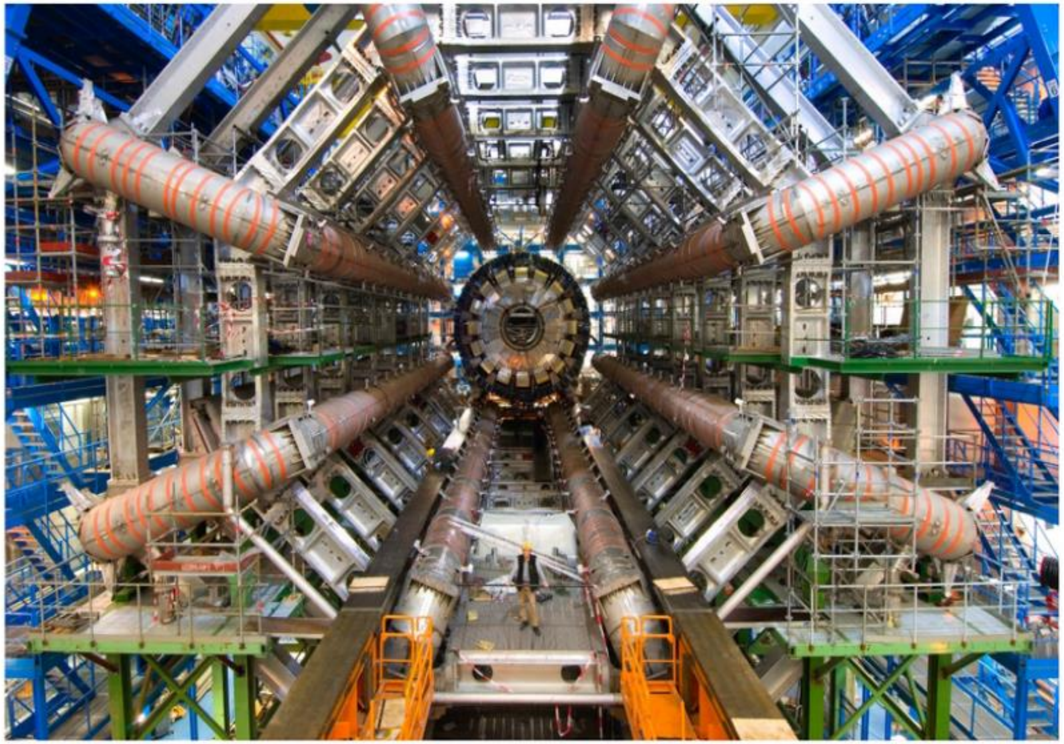
- Outer Part of ATLAS, identifies and measures the momenta of muons.

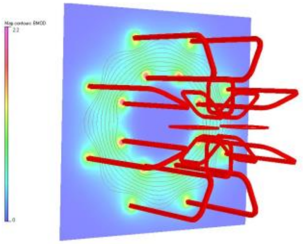


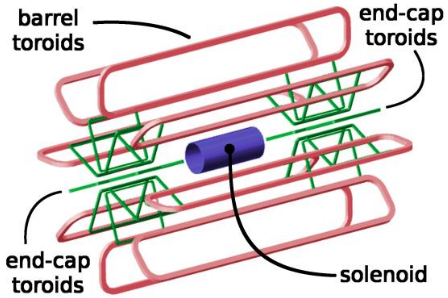


ATLAS components 4: Magnets System

- Bends particles around the various layers of detector systems
- Central Solenoid Magnet 2T.
- Barrel and End-cap Toroids of about 0.5-1 T.



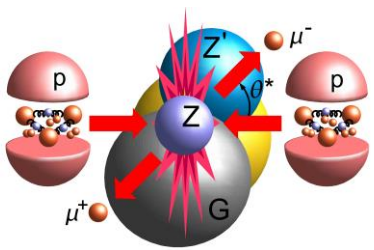




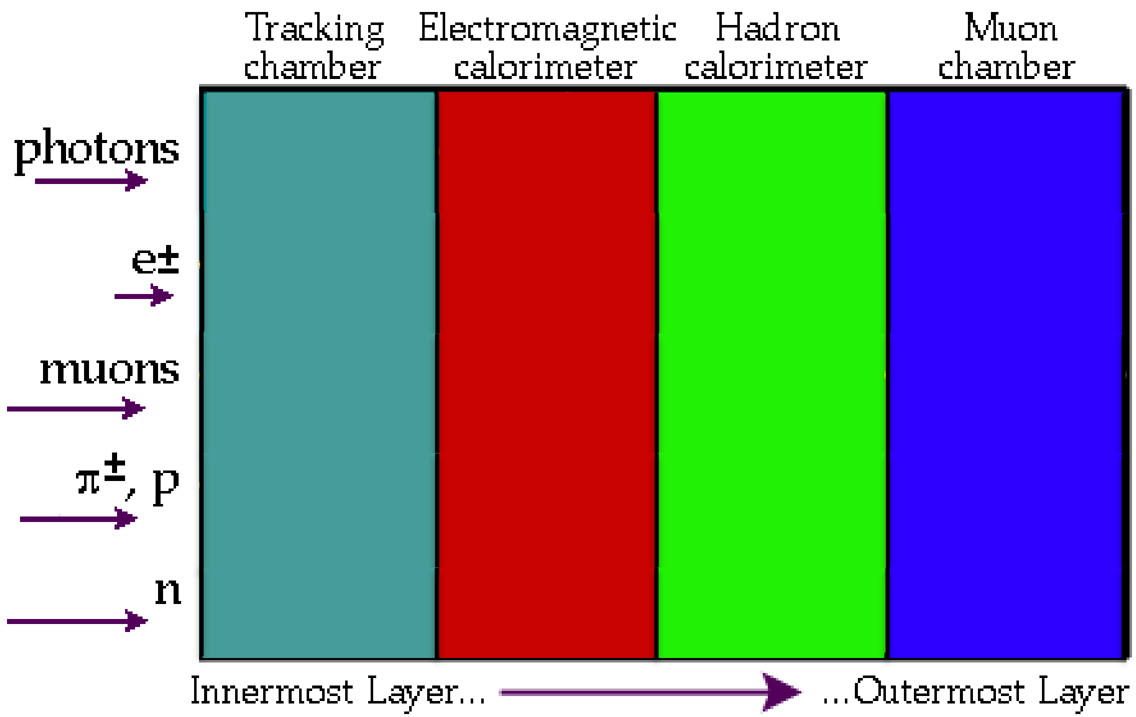
Combining Information

Charged particles leave a track

Hadrons make a hadronic shower



Collision



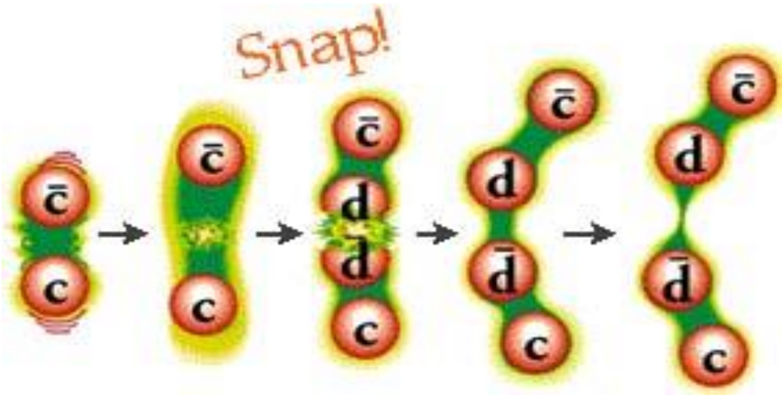
Electromagnetically interacting particles make an electromagnetic shower

Muons don't interact much. Luckily they are charged!

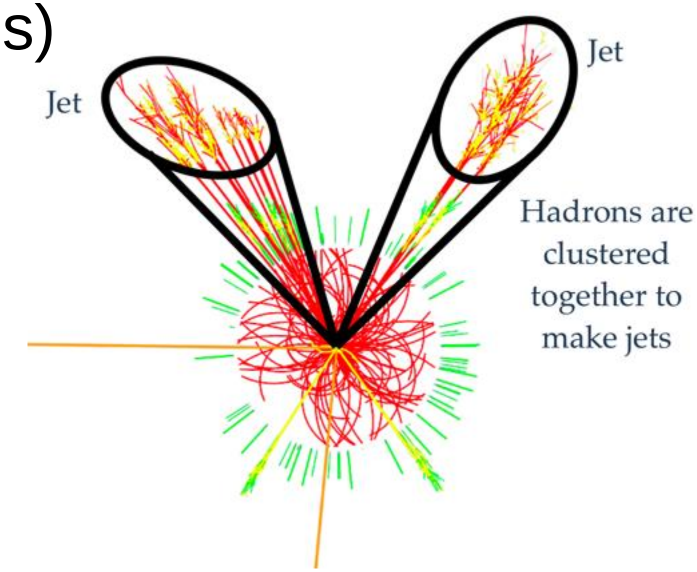
Particle Jets from Quarks

Quarks can not exist alone !

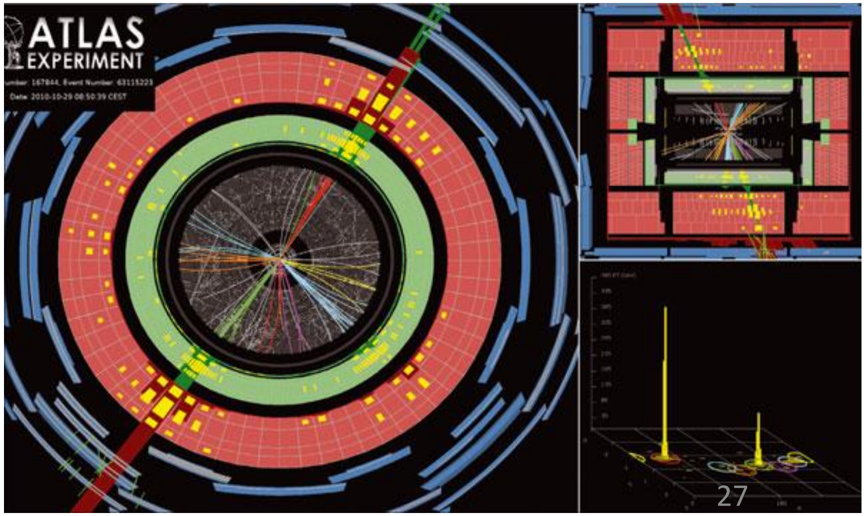
Quarks moving apart create new quark-pairs



Then these quarks form hadrons flying all in one direction (a jet of hadrons)



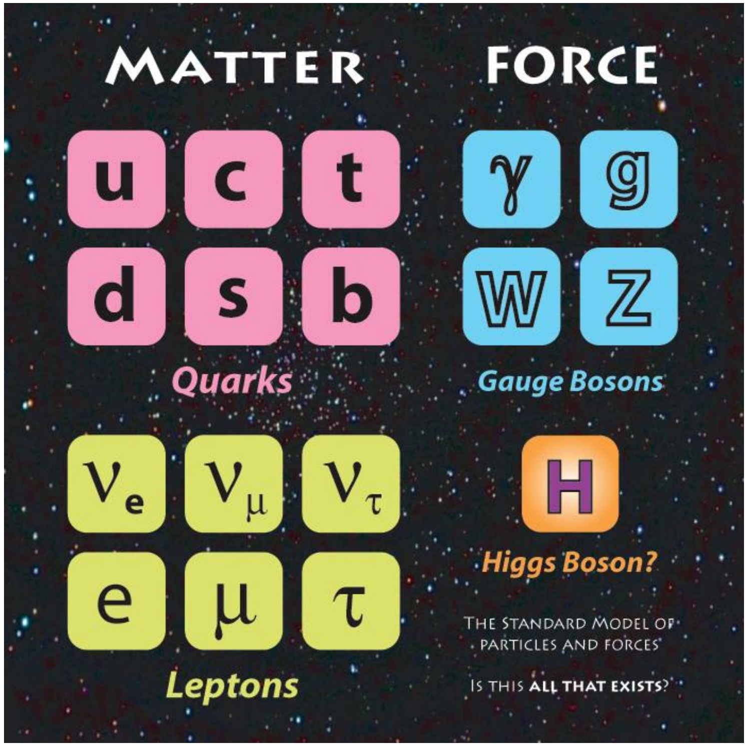
Two jets observed in the ATLAS hadronic calorimeter



Did we forget something ?

Photons ✓

Quarks ✓



Tau, Gluons, W, Z, H

Short lifetime

Electrons ✓

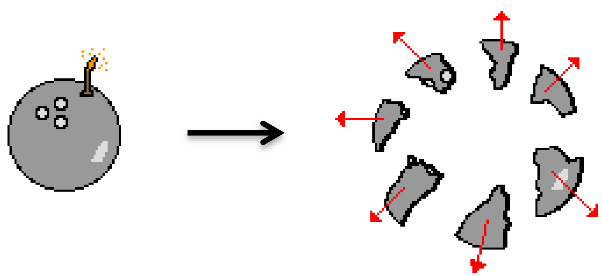
Muons ✓

Neutrinos ?

How to find Neutrinos ?

Neutrinos are invisible (they don't interact)

If you measure everything you can see, any imbalance you see must be from a neutrino!

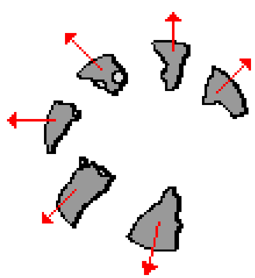


$$\sum \vec{p}_{T\,i} = 0$$

The total (transverse) momentum must be 0!

Momentum conservation in a explosion !

Not possible to know how many neutrinos



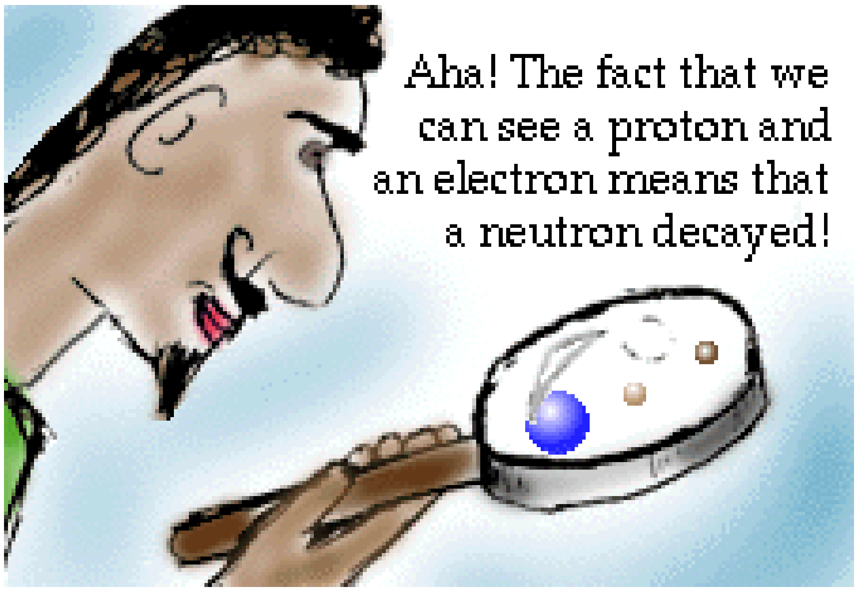
$$\sum \vec{p}_{T\,i} \neq 0$$

A neutrino escaped undetected !

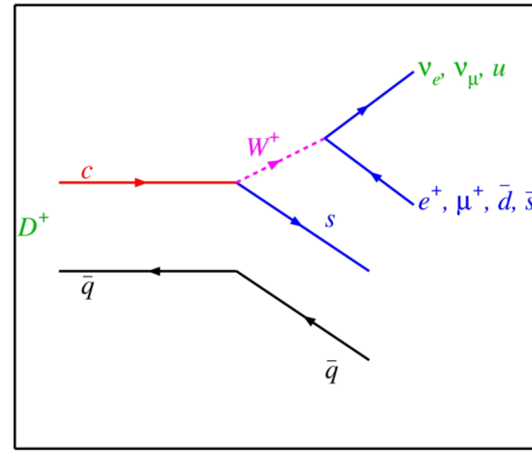
ATLAS Shockwave animation

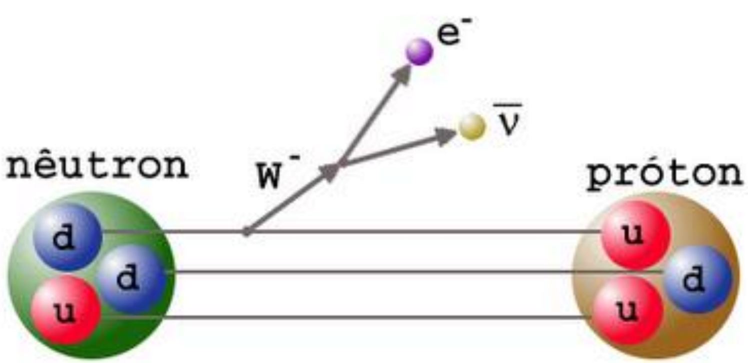
Becoming a Particle Detective

Most particles live very short. Have to deduce them from the final decay products.

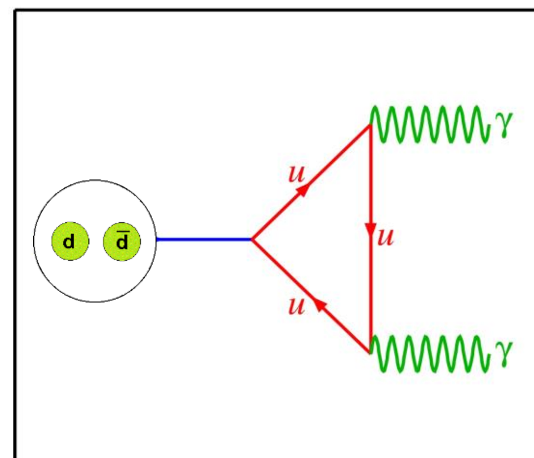


A D^+ meson decays into a K meson and a W^+





π^0 Decay

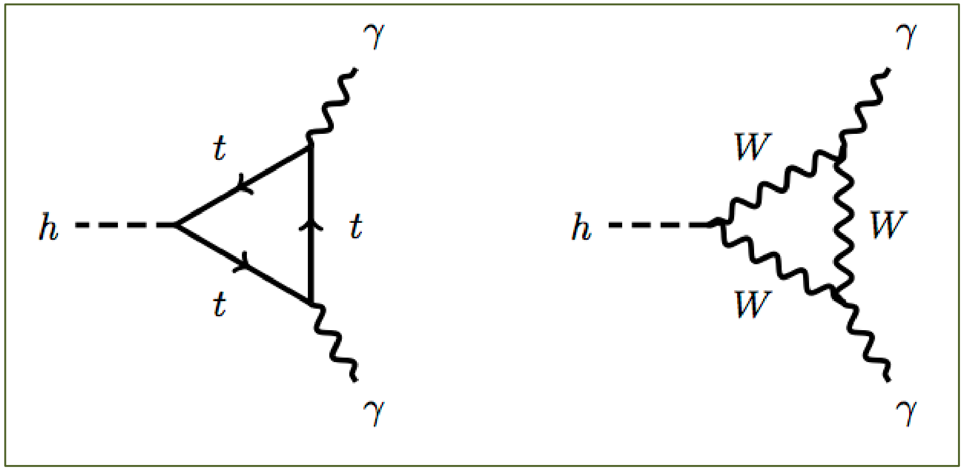


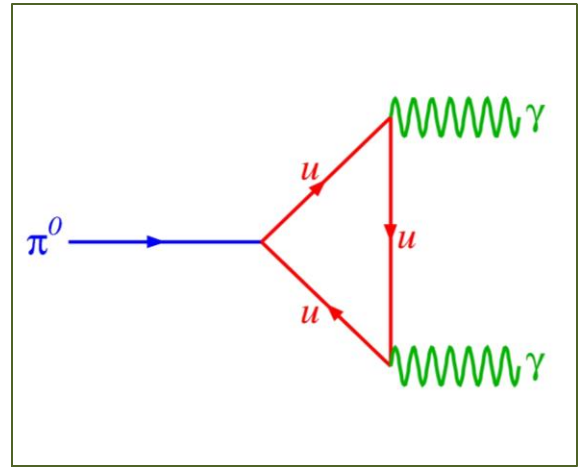
A π^0 meson decays into two photons

Becoming a Particle Detective Part II

Knowledge of final decay products is not enough

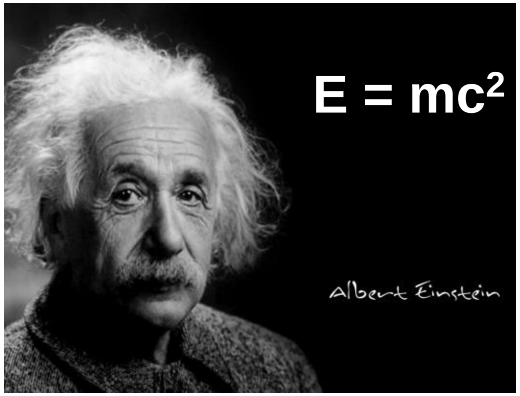
Higgs and π^0 both can decay into 2 photons





We must also determine the original mass of the $\gamma\gamma$-system

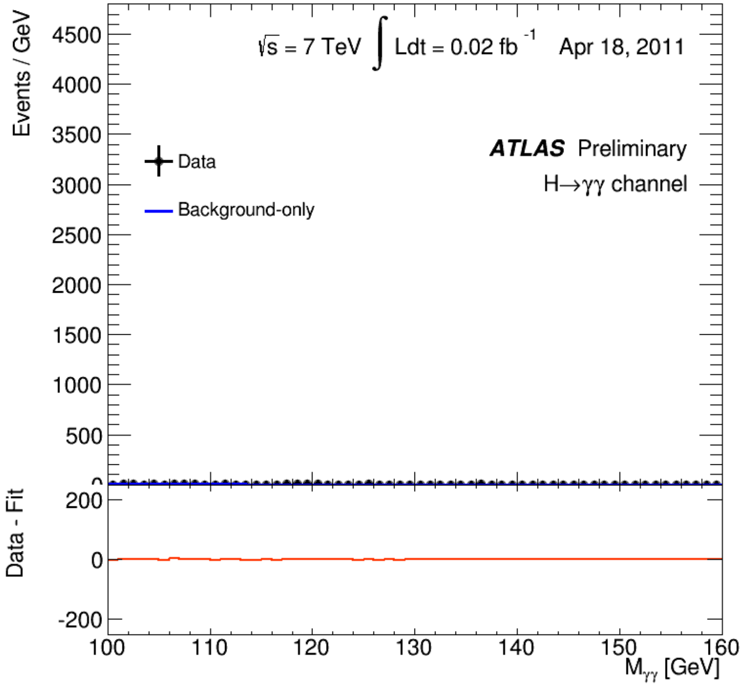
Becoming a Particle Detective Part II



Energy conservation +

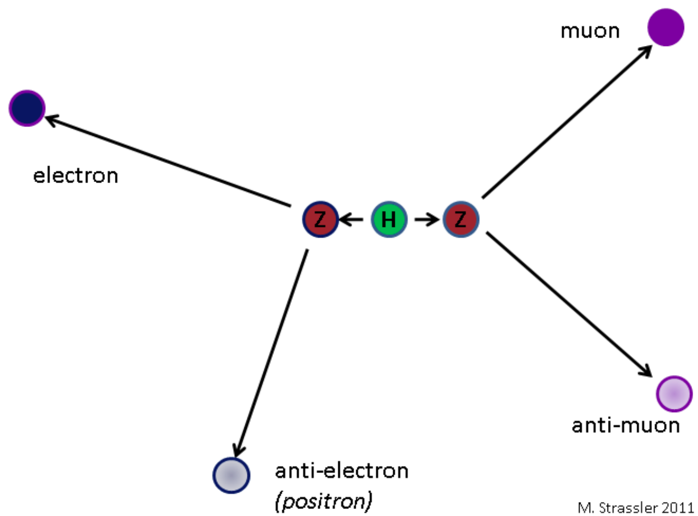
momentum conservation +

$$M_{inv} = \sqrt{\left(E_{\gamma 1} + E_{\gamma 2}\right)^2 - \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right)^2}$$

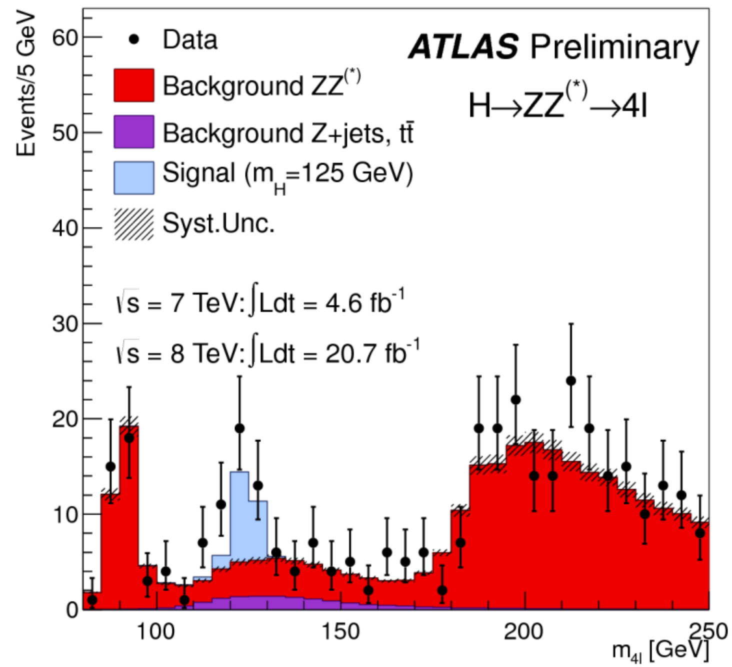


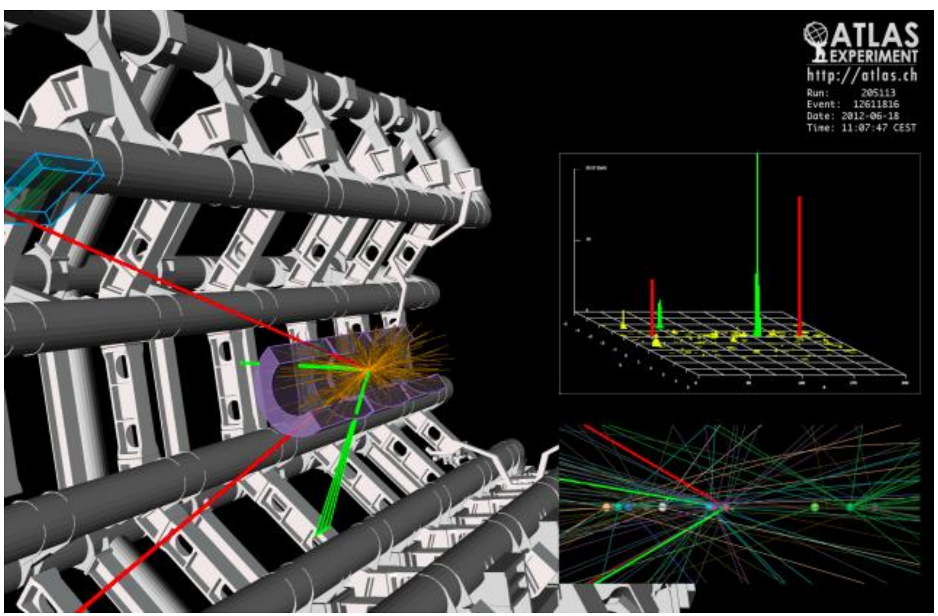
Higgs mass around 125 GeV

Another Higgs Decay – The Golden Mode



Higgs → 2 Z → 4 leptons





ATLAS H→4l with 2 years of data

QUESTIONS