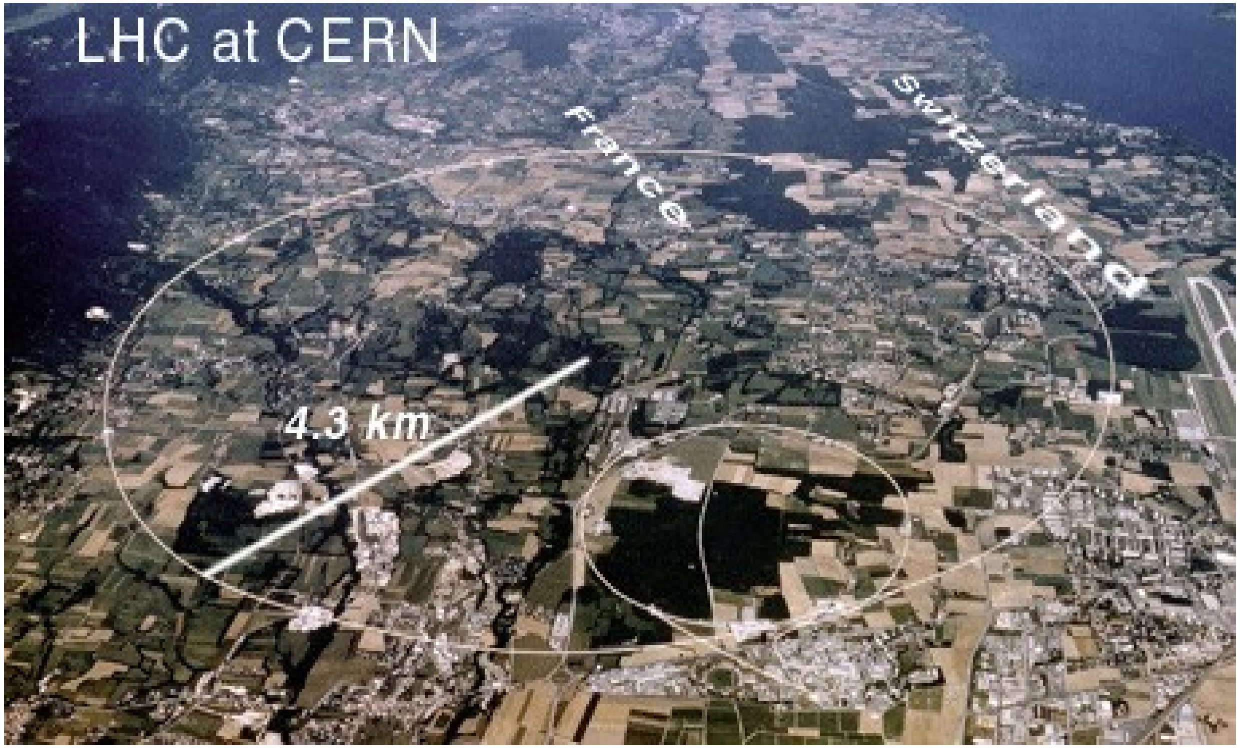
LHC experiment.



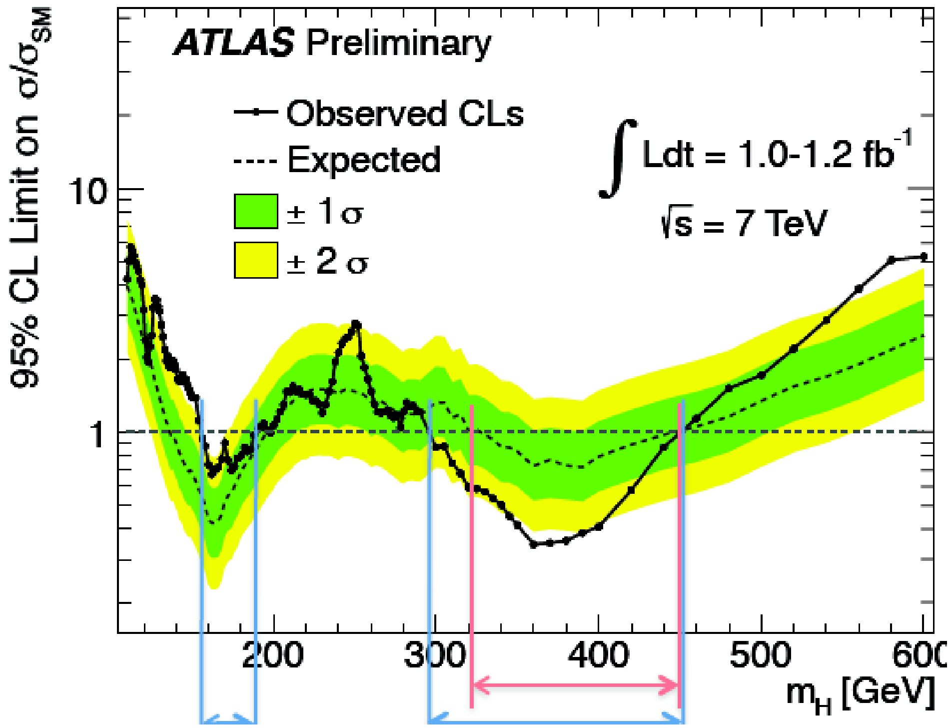
Summer student lectures, DESY Zeuthen 2011

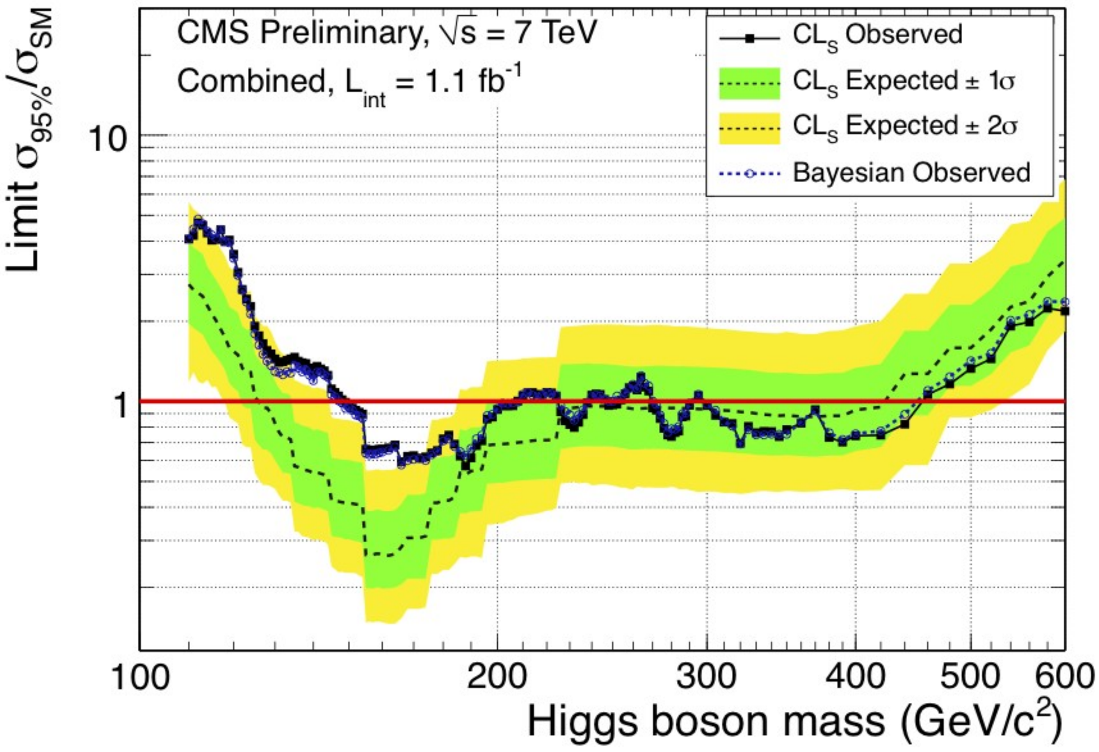
Elin Bergeaas Kuutmann

Some recent news...

Presented at the EPS conference, Friday 22 July

- Is this a discovery of the Higgs boson?
- If not, what is it?
- After the lectures today and tomorrow, you will be able to interpret the plot, understand what it shows, how it was deduced and answer the questions above.





Overview of lecture 1

- Why do experiments with colliding particles?
- Particle physics overview
- Accelerator and detector concepts
- The LHC experiments
- How to detect and identify particles

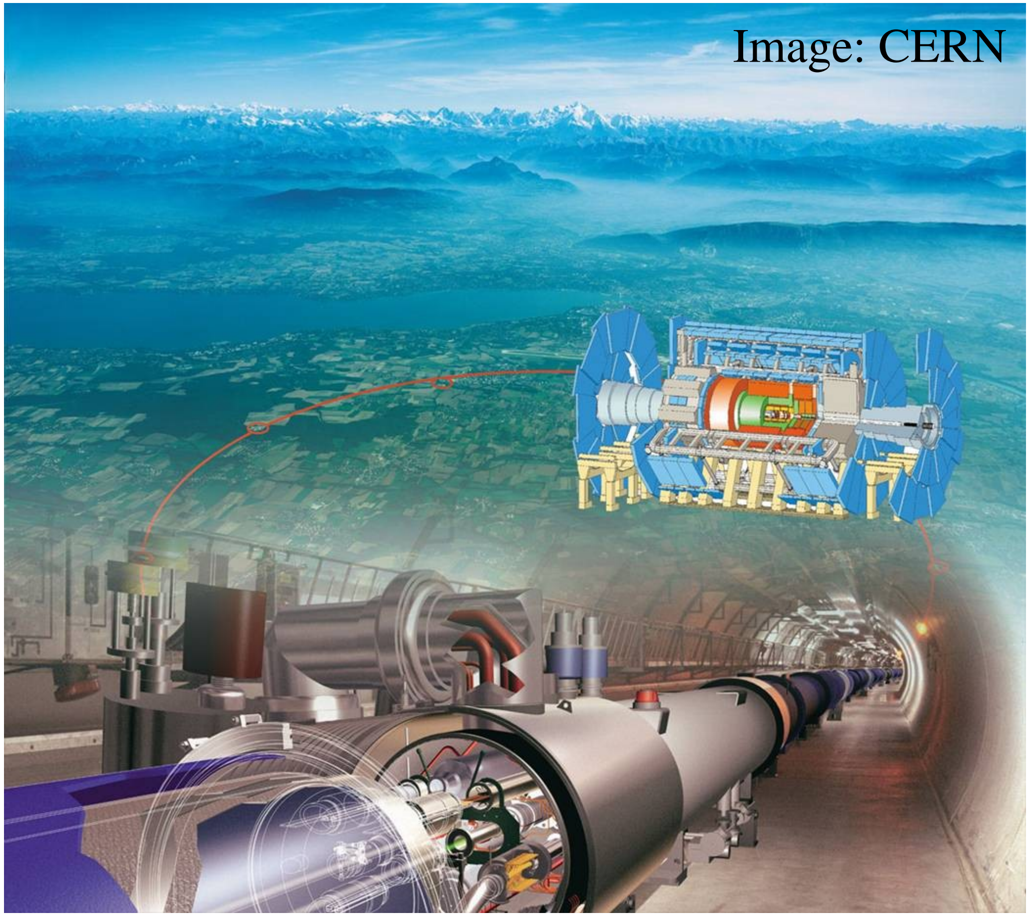


Image: CERN

WARNING! The author of these slides has worked with ATLAS for 7 years! ATLAS bias imminent!

Why?

- All we know for sure about reality is founded in experiments and observations:
  - We poke at something and look at the result.
  - If someone else can poke at another sample of the same thing with the same result, the experiment has been **reproduced**.
  - We only trust reproducible results.

- Experiments have shown that
  - there are atoms, consisting of electrons and nucleons, that consist of quarks and gluons,
  - the weak force is mediated by gauge bosons,
  - there are (at least) 6 quarks and exactly 3 light neutrinos,
  - ...

Why more experiments?

- Most things are still unknown!
  - What is the dark matter?
  - Is there a Higgs boson, and if not, where does the mass come from?
  - Why 3 generations of matter?

In a collider experiment,
we create the particles
in a controlled environment.

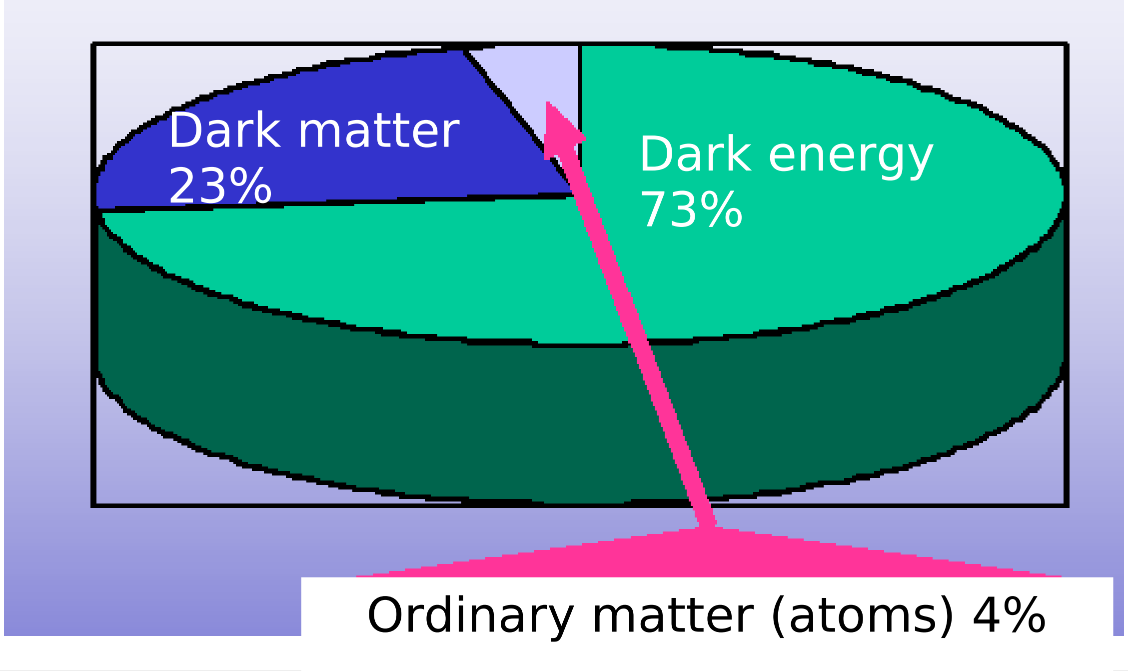


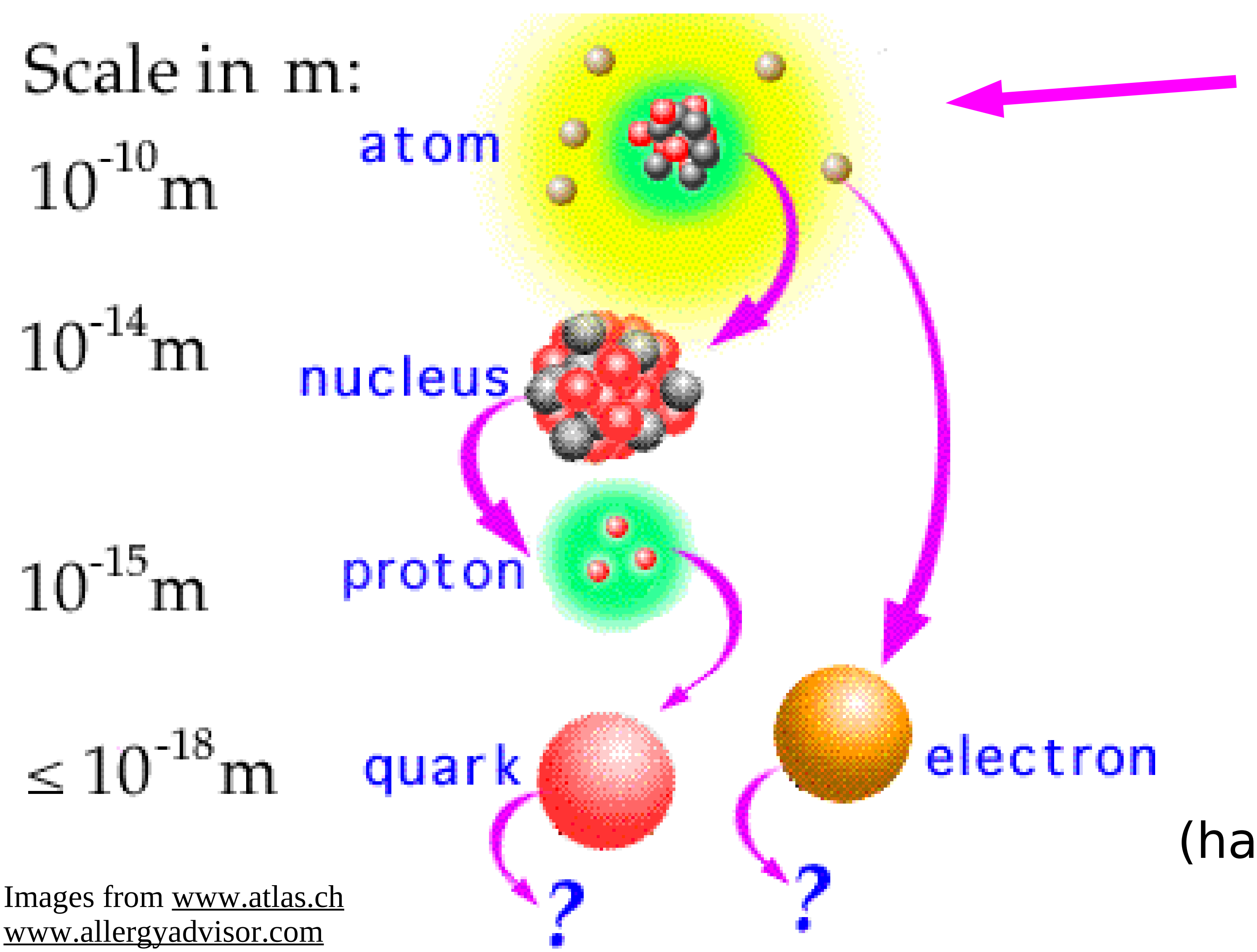
Photo: Chandra X-ray Observatory

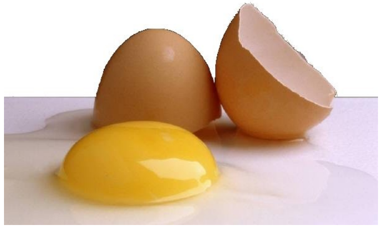
Particle physics overview

Matter and forces

Elementary particle physics

the matter around us



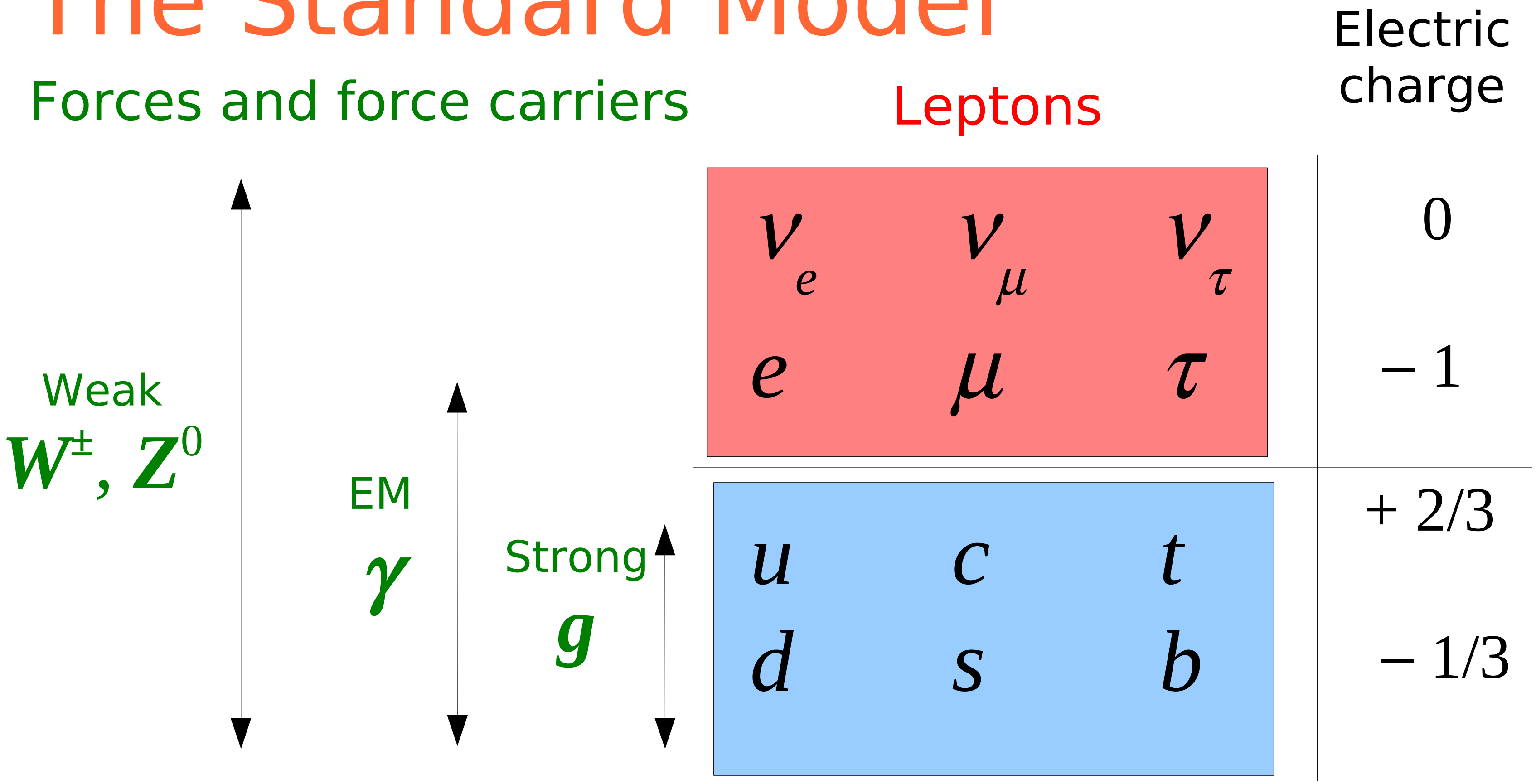


Egg: 10^{-1} m

Matter:
leptons
(electrons, ...)
quarks
(hadrons: protons, neutrons...)

Images from www.atlas.ch
www.allergyadvisor.com

The Standard Model



Forces and force carriers

Weak
$W^{\pm}, Z^{0}$

EM
γ

Strong
g

Leptons

			Electric charge
ν_e	ν_μ	ν_τ	0
e	μ	τ	– 1
u	c	t	+ 2/3
d	s	b	– 1/3

Quarks
combine to **hadrons**

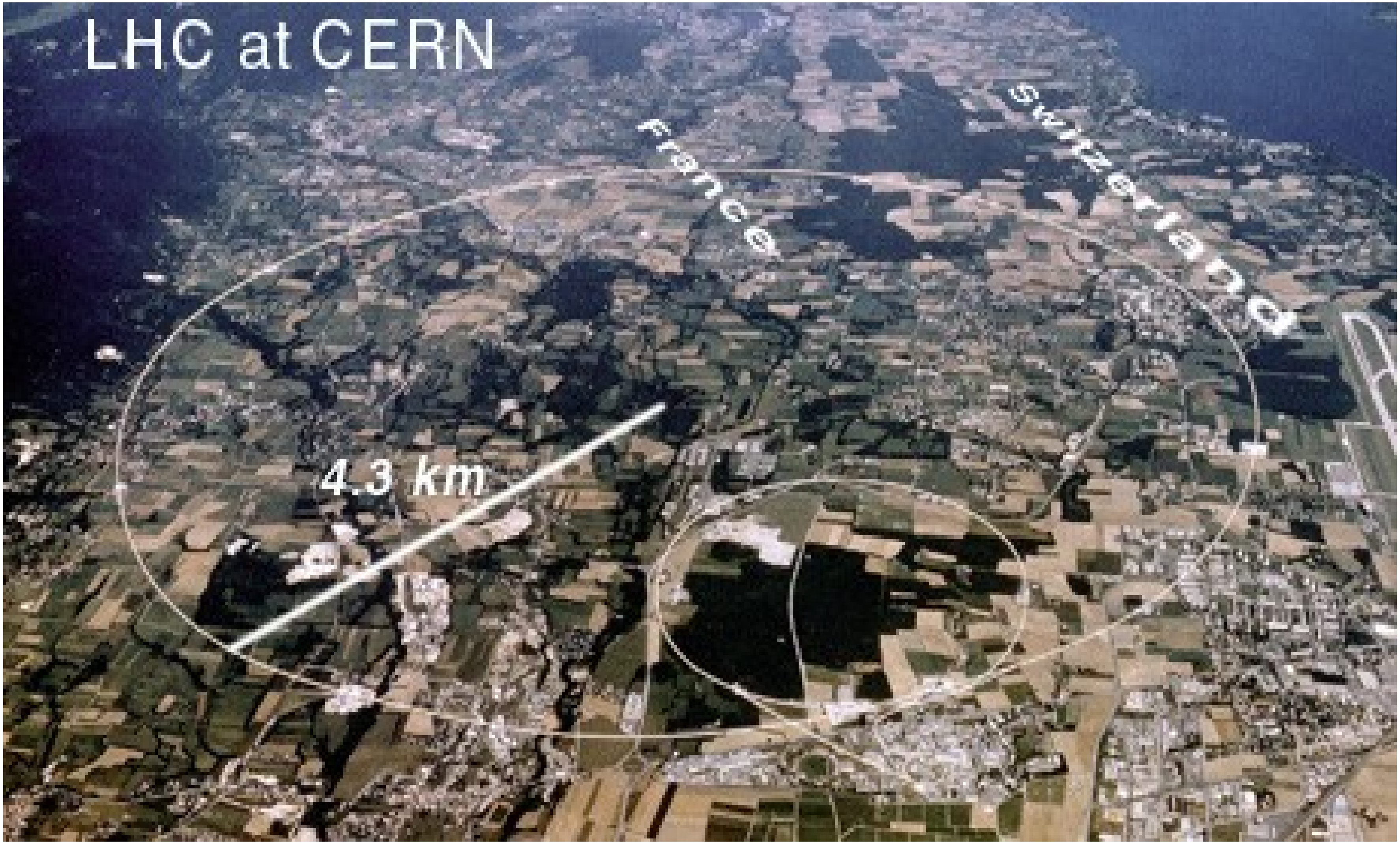
Gravity is not included in SM (negligible on the sub-atomic level).
The Higgs boson is needed to explain the particle masses;
not (yet) experimentally verified.

Accelerator and detector concepts

LHC
Tera-electron volts
Hadron vs. lepton colliders
Why high energies
Colliding beams and fixed target
Detector geometry
The event
How much: cross secition and luminosity

LHC at CERN

The Large Hadron Collider is situated near CERN outside Geneva, on the Swiss/French border, approximately 100 m under the ground.



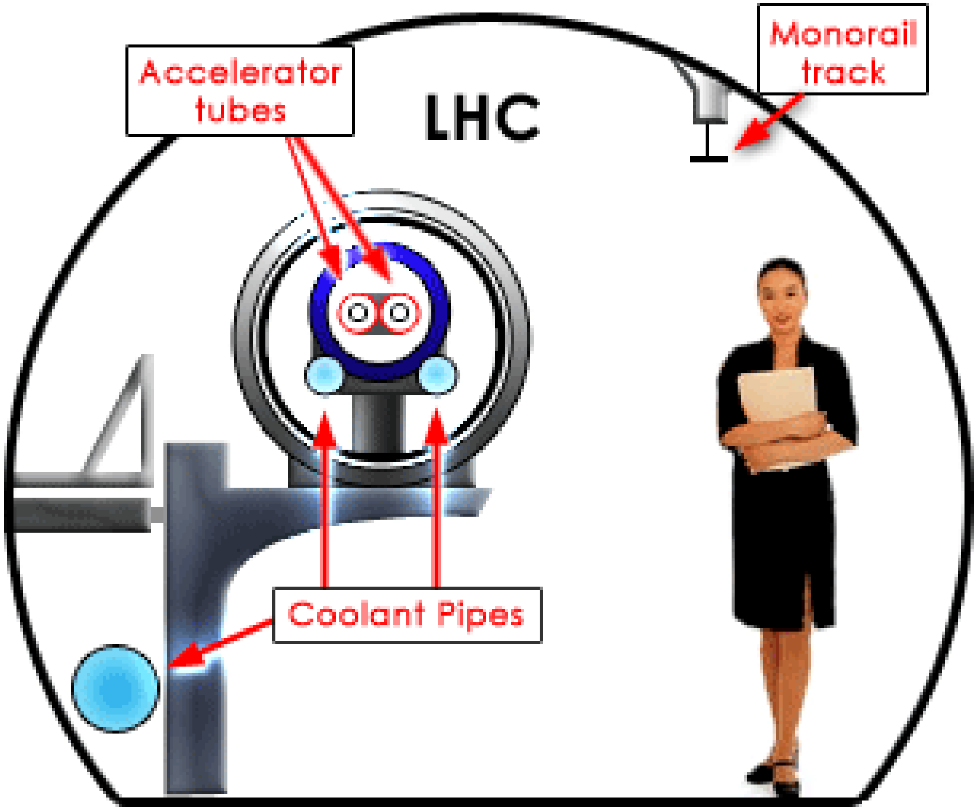
The accelerator

LHC (Large Hadron Collider) collide protons or lead ions. Started in Sept. 2008, restarted in March 2010.

Current collision energy 7 TeV, designed for 14 TeV.

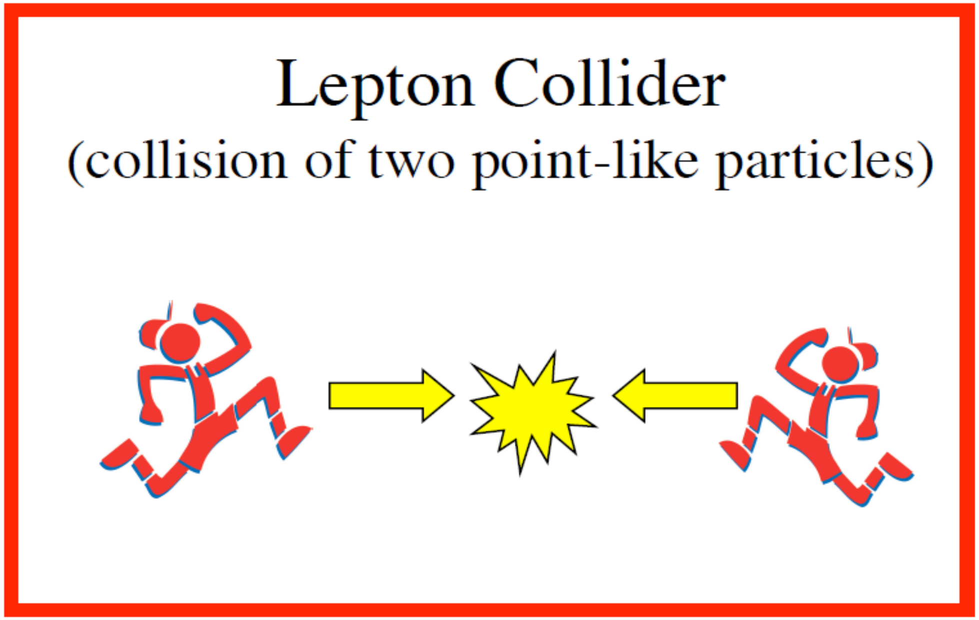
LHC is the largest hadron collider ever built, outperforming even the Tevatron in Chicago (proton-antiproton collider, collision energy 1.96 TeV).

Cross section of the LHC tunnels.
Note the two beam pipes!

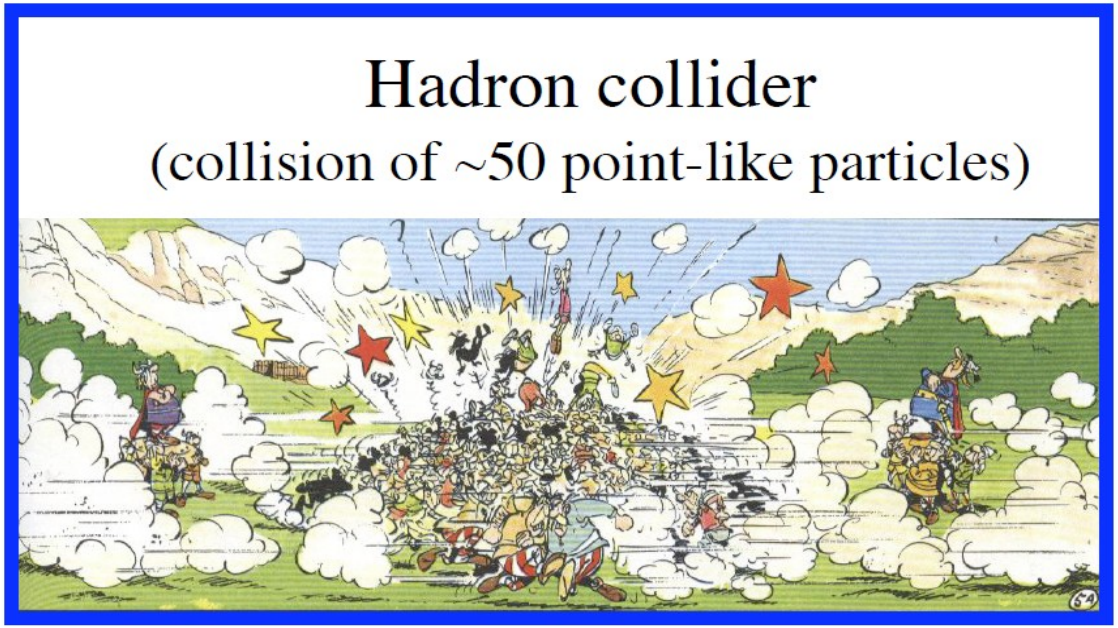


Animation from www.atlas.ch

Hadron and lepton colliders



Lepton Collider
(collision of two point-like particles)



Hadron collider
(collision of ~50 point-like particles)

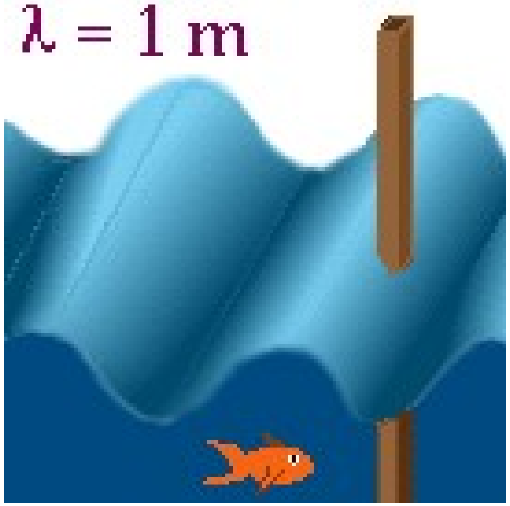
(K. Jakobs)

- Lepton collisions: cleaner
- Hadron collisions: higher energies available (protons more massive than electrons) but also busier events.

Activation break 1:

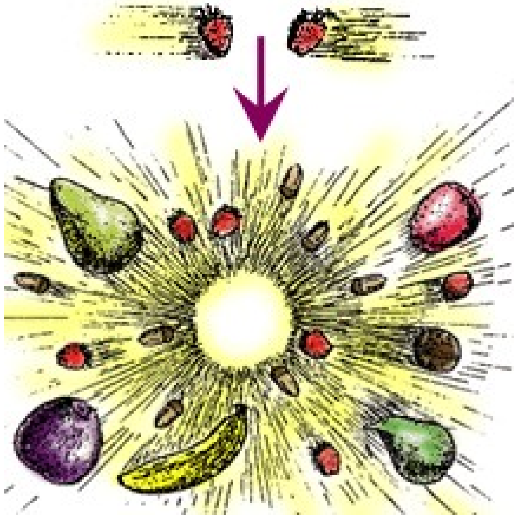
Why high energies?

- Look at small structures $\lambda = h / p$,
  particles with high energy (momentum) have short wavelengths.



- Create new heavy particles, $E = mc^2$
  When light particles collide at high energies, the excess energy can be used to create new particles.

Note: normally we use natural units, $c = \hbar = 1$. Then we can give masses and momenta in GeV.

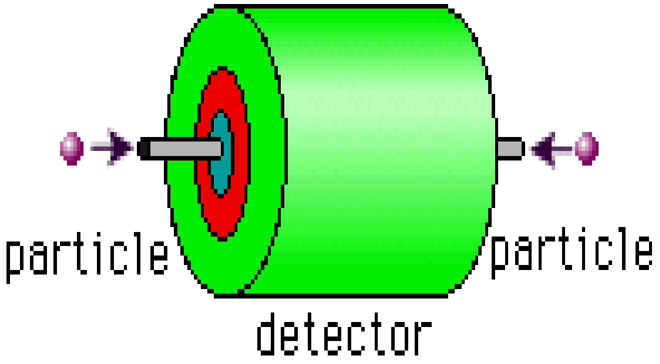


Images from particleadventure.org

Detector concepts

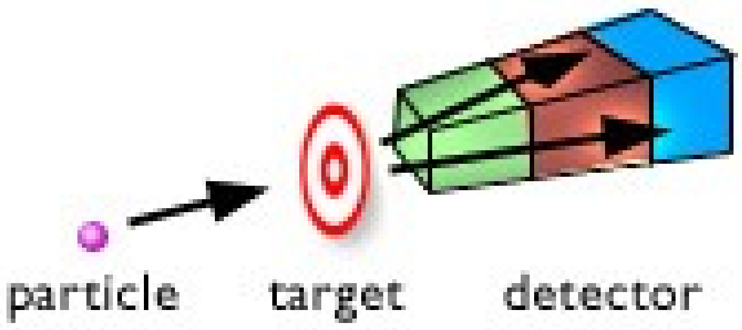
Images from www.atlas.ch

We create new particles with the collider: need detectors to see them!



Barrel-shaped detectors (hermetic) for colliding beams.

$$E_{CM} = E_{beam} + E_{beam}$$



Wedge-shaped detectors for fixed-target experiments

$$E_{CM} = \sqrt{2 m_{proton} c^2 \cdot E_{beam}}$$

The region roughly parallel to the beam line is the ***forward*** direction. The region roughly perpendicular to the beam line is the ***central*** region.

All the major LHC experiments are colliding-beams experiments, and most have barrel-shaped hermetic detectors.

Detector geometry, rapidity and pseudorapidity

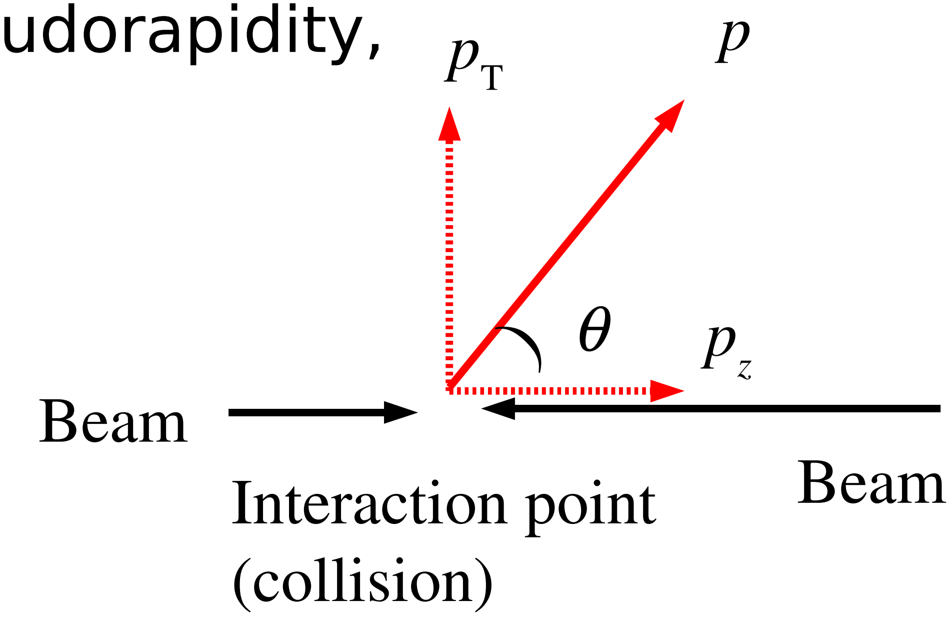
- The rapidity y_r from the longitudinal momentum p_z

$$y_r = \frac{1}{2} \log \frac{E + p_z}{E - p_z}$$

Rapidity differences are Lorentz invariant.

- Transverse momentum: $p_T = \sqrt{p_x^2 + p_y^2}$
- For massless particles, the pseudorapidity, η is equal to y_r

$$\eta = -\log \tan \left(\frac{\theta}{2} \right)$$



Note that η is computed from geometry only!

$|\eta| \to \infty$: along the beampipe

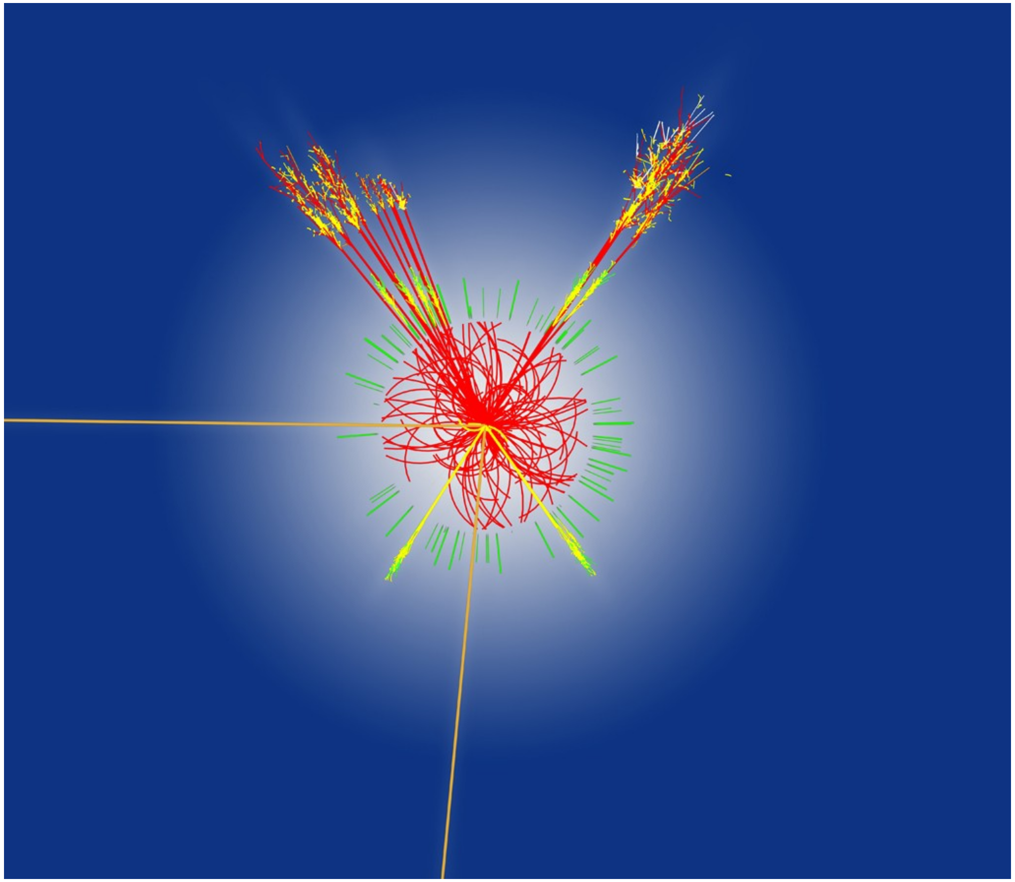
$|\eta| = 0$: perpendicular to the beam

- ϕ is the azimuthal angle (around the beampipe)

The event

- In collider physics terminology, an event is a particle collision, i.e. something that happens.
- It could also be a particle decay, a cosmic ray...
- When LHC is operating at design capacity, there will be 1 billion events (proton-proton collisions) per second in ATLAS and CMS each.

Image: atlas.ch



A (simulated) Higgs event.

Cross section

- The cross section (σ) is a measure of the probability of a certain process occurring.
- Measured in units of area (typically cm^2 or barn = 10^{-24} cm^2).
- Visually this can be seen as the area the incoming particle must hit in order for an interaction to happen.
  This is only true classically.
- In LHC for $\sqrt{s}$ = 14 TeV,
  the total inelastic pp cross section is $79 \cdot 10^3$ pb (pico-barn).
  The top-anti top cross section is 794 pb.

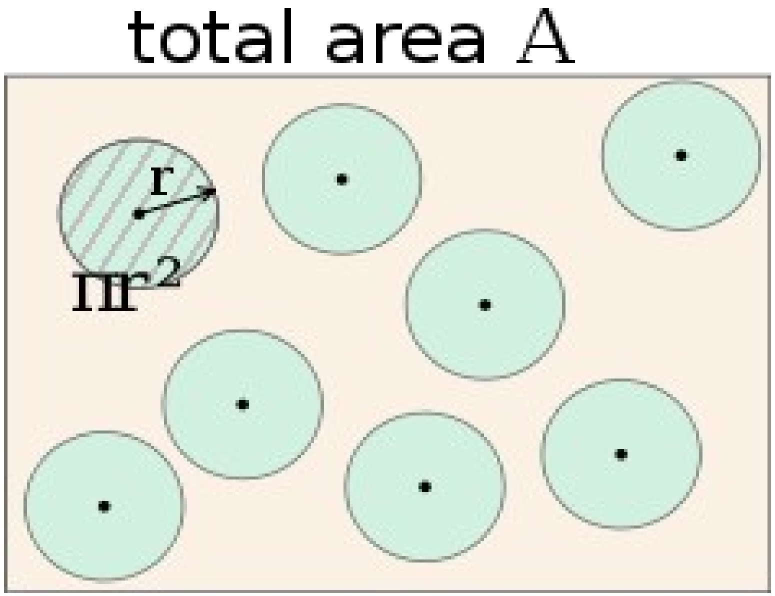


Image: wikipedia.org

Luminosity

- Defines the intensity of the beam collisions.
- The number of observed events *N* is

$$N = A\,\epsilon\,\sigma \int L\,dt$$

Detector property

Optimised by experimentalist

From nature (theoretically computed)

A: acceptance,
ε: selection efficiency
σ: cross section,
L: luminosity, integrated over time *t*.

- *L* is defined from the properties of the accelerator, and carefully measured during data-taking.

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\,\sigma_x\,\sigma_y}$$

LHC design:
revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p = 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm^2

(B. Heinemann)

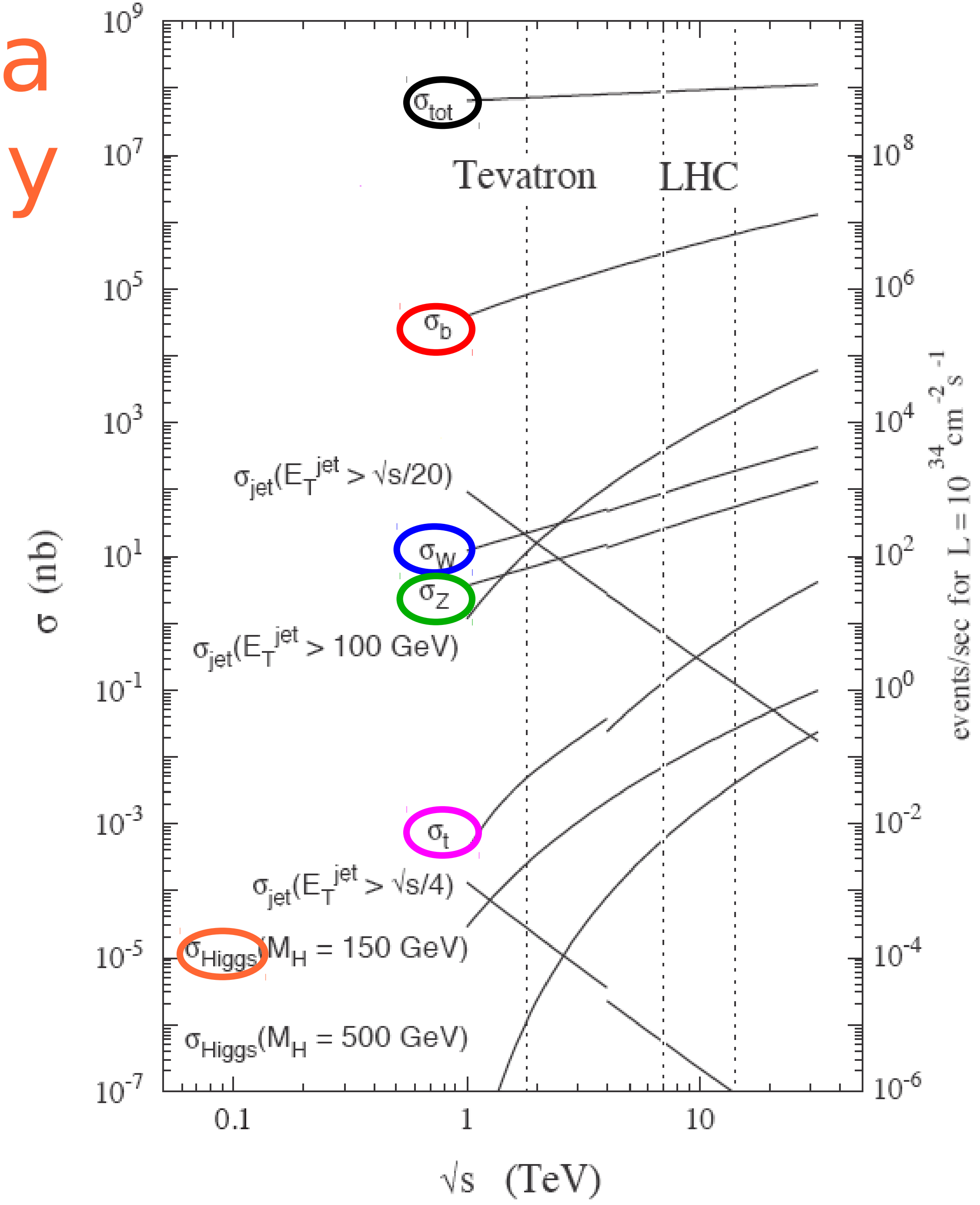
Luminosity and cross section

- **Integrated luminosity** – the instantaneous luminosity integrated over time: the total amount of data collected. Unit: inverse area.
- *Example:* If the data sample is 100 pb^{-1} and the cross section for producing particle X is 1 pb, the sample contains (on average) 100 particles X.
- NB! 1 fb^{-1} is 1000 times more than 1 pb^{-1}.

The Tevatron experiments have about 8 fb^{-1} of collected data. ATLAS and CMS has more than 1 fb^{-1} recorded this year. LHC is aiming for several fb^{-1} before the end of 2011.

Cross section as a function of energy

- Total (anti)proton-proton collision cross section
- b-quark
- W boson
- Z boson
- top quark
- Higgs (M=150 GeV)



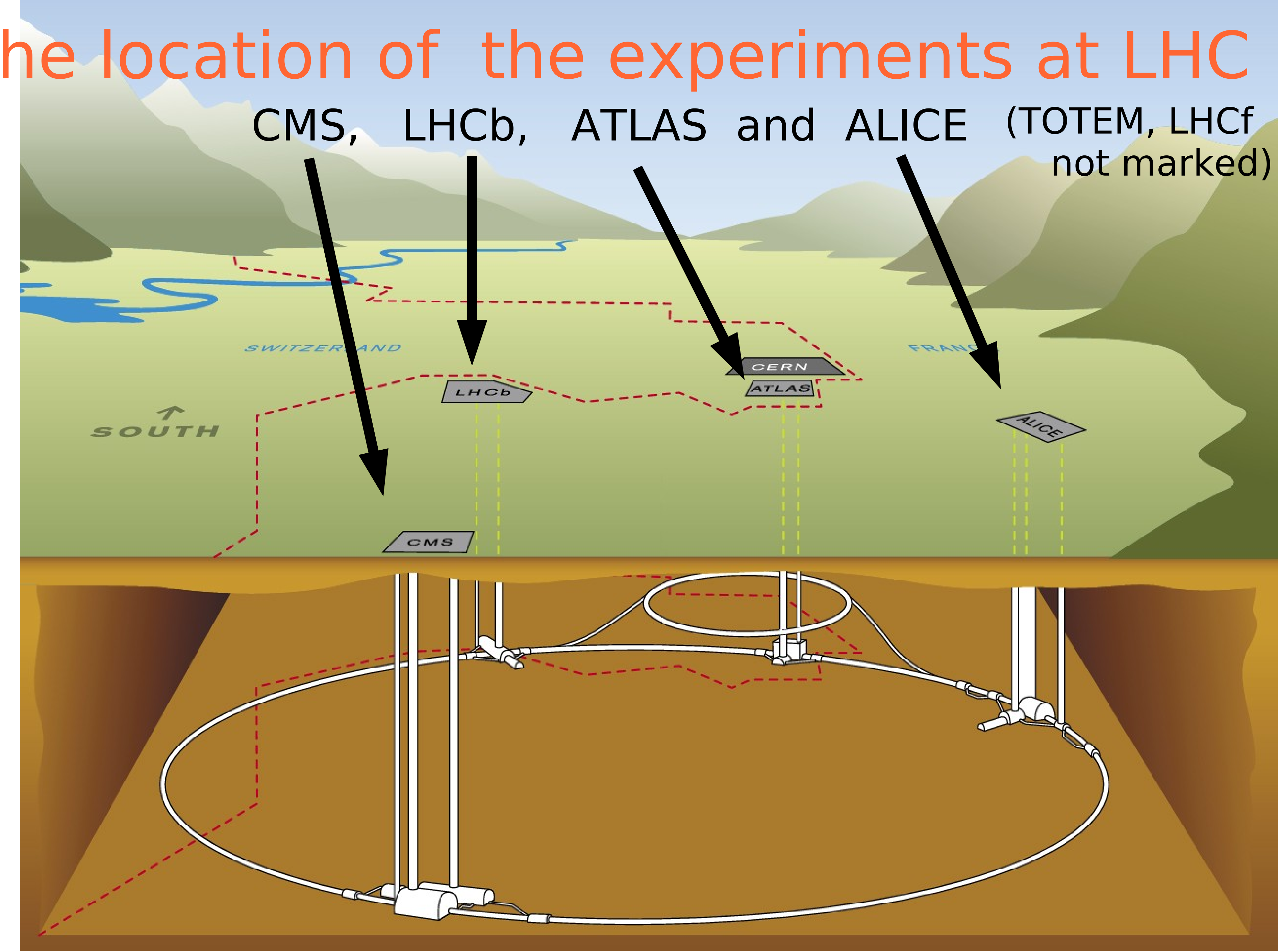
From the ATLAS TDR (2003)

Activation break 2:

The LHC experiments:

ATLAS, CMS
LHCb, ALICE
TOTEM, LHCf

The location of the experiments at LHC



CMS, LHCb, ATLAS and ALICE (TOTEM, LHCf not marked)

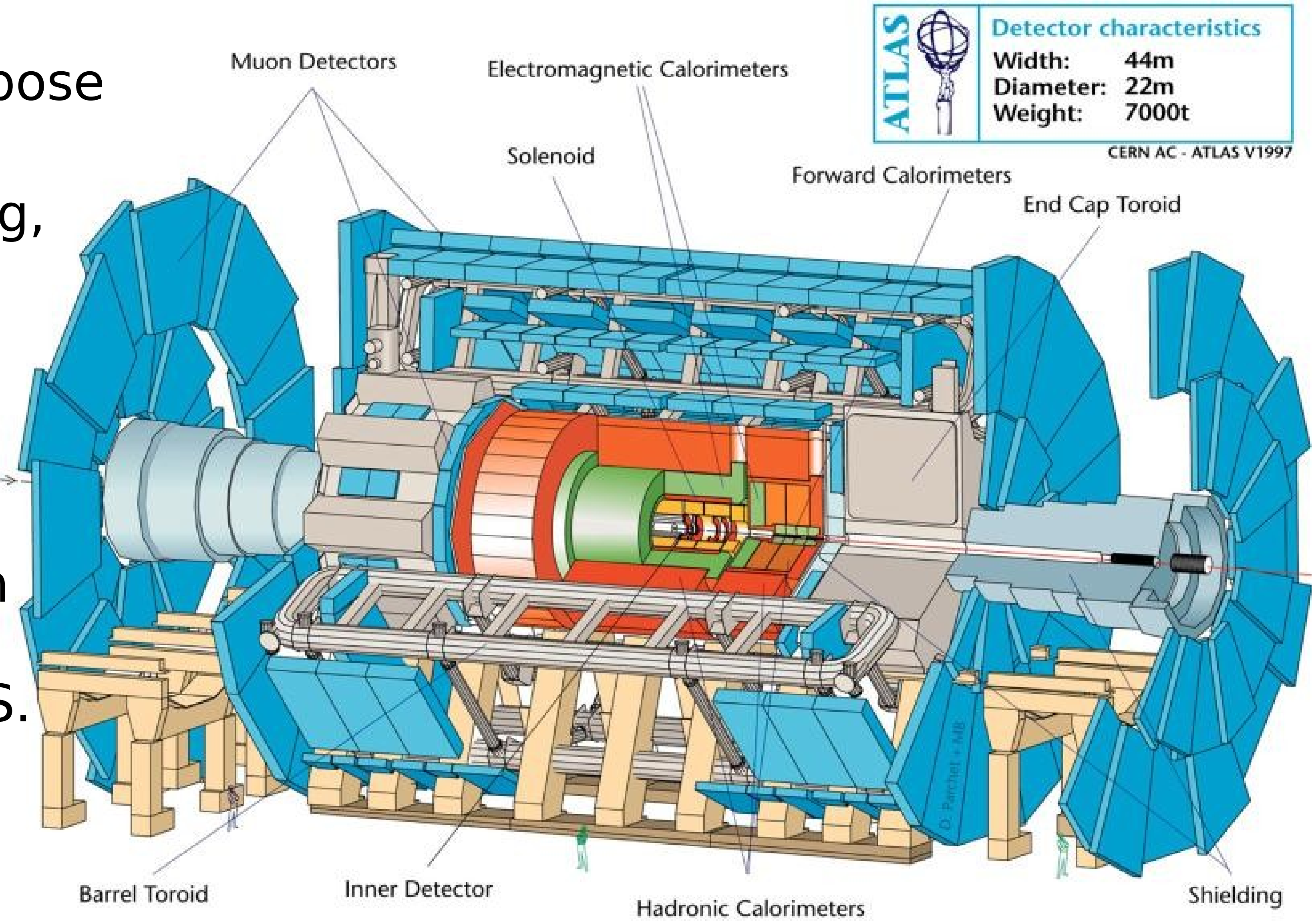
ATLAS – A Toroidal LHC ApparatuS

Image from www.atlas.ch

A general-purpose detector.

Size: 44 m long,
 22 m high
 22 m wide.
Weight:
7000 tonnes.

3000 scientists from 38 countries work on ATLAS.



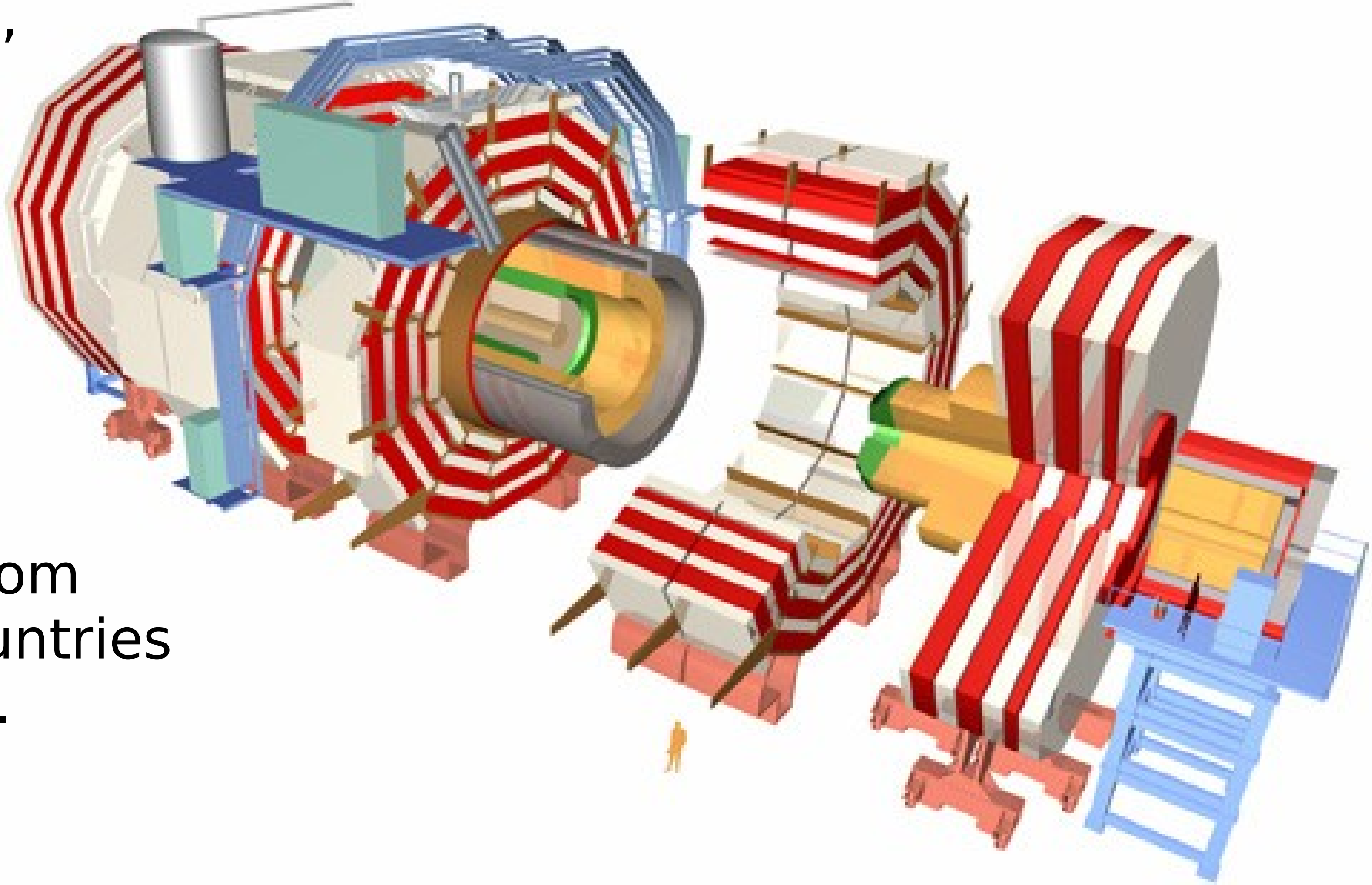
CMS – Compact Muon Solenoid

A general-purpose detector.

Size: 21 m long,
15 m wide
15 m high.

Weight: 12 500 tonnes

More than 2000 scientists collaborate in CMS, coming from 37 different countries (October 2006).



A size comparison...

(B. Heinemann)

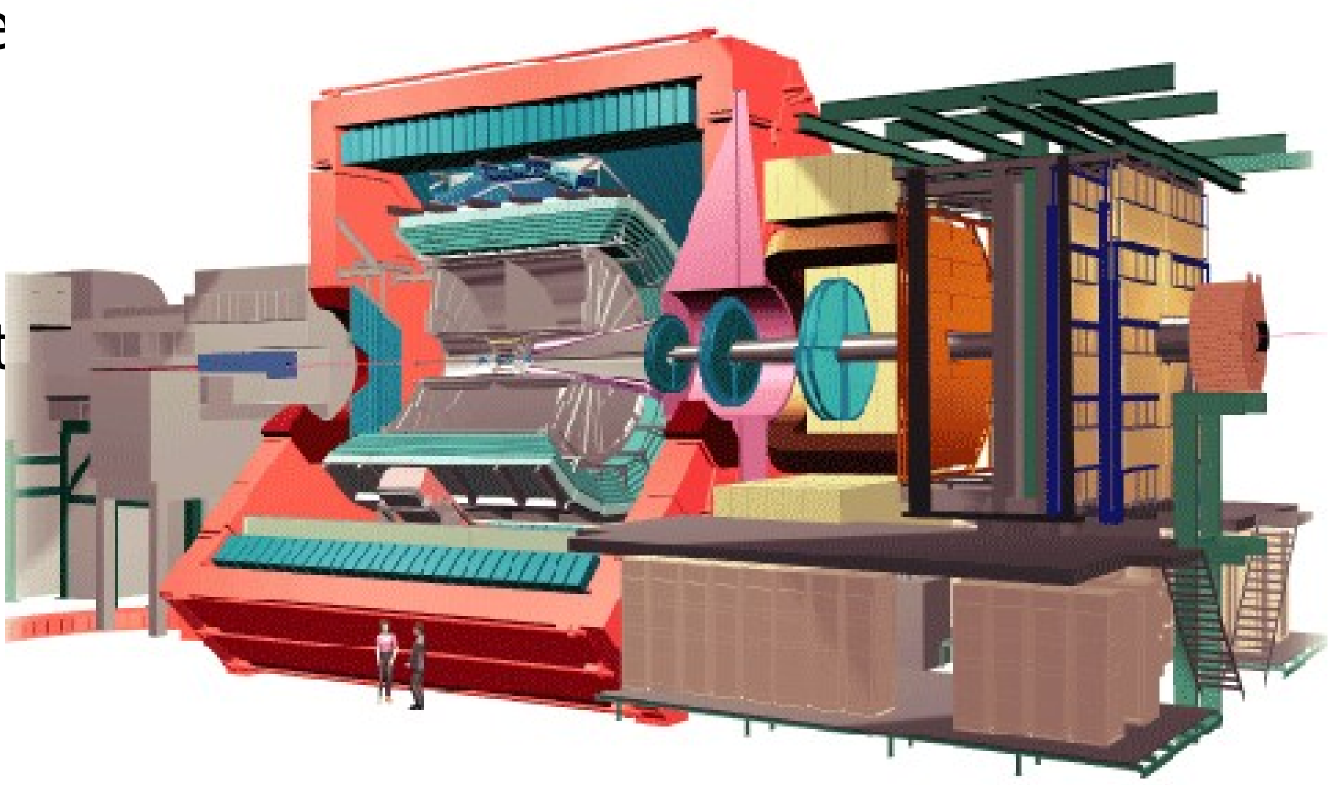
ALICE – A Large Ion Collider Experiment

Will study lead ion collisions: recreate the conditions just after the Big Bang; quark-gluon plasma.

Size: 26 m long, 16 m high, 16 m wide

Weight: 10 000 tonne

More than 1000 scientists from 28 countries works on the ALICE experiment (March 2006).



LHCb

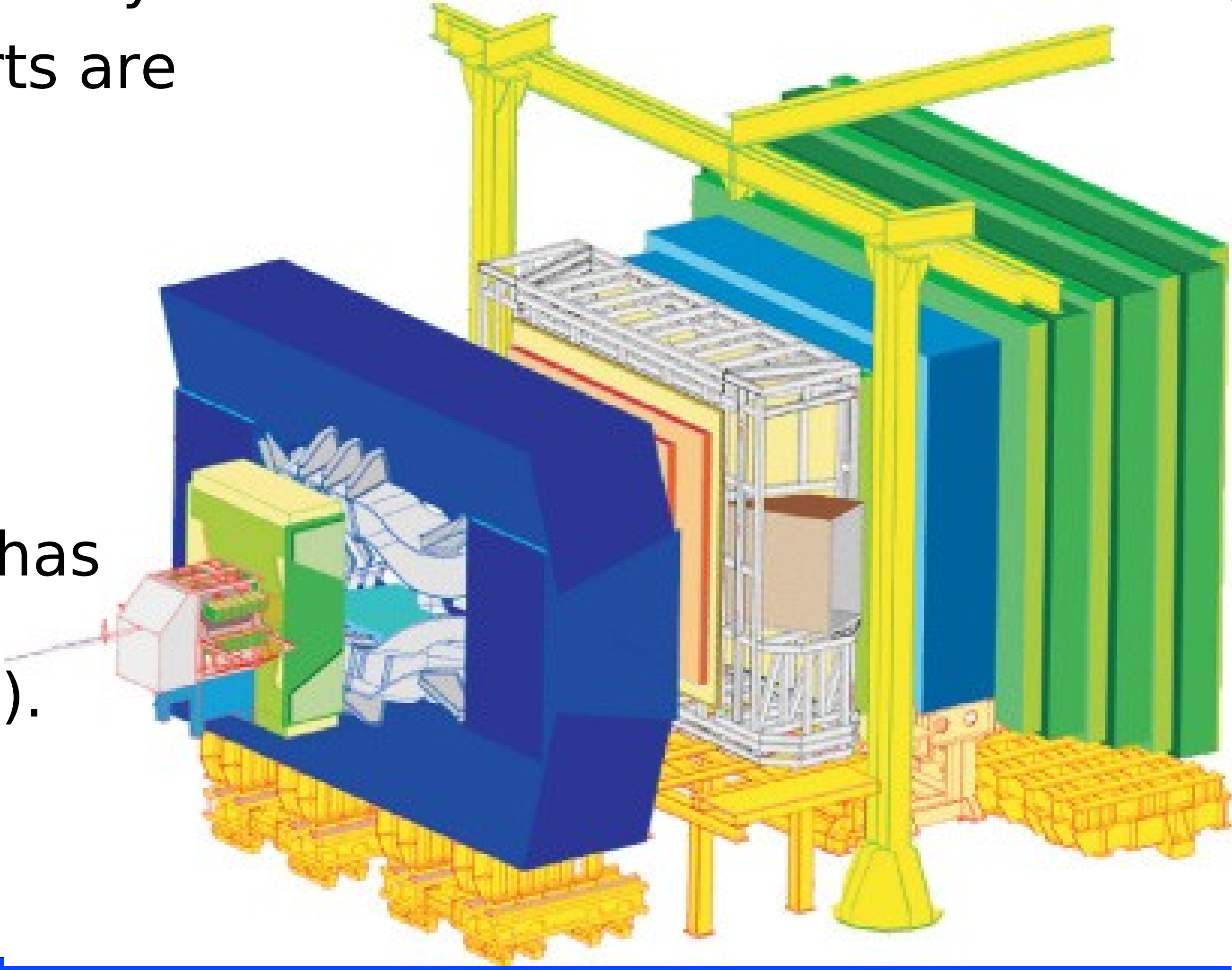
Designed to study the b quark in order to investigate the matter-animatter asymmetry in the universe.

Most of the detector parts are in the forward direction.

Size: 21m long,
10m high
13m wide

Weight: 5600 tonnes

The LHCb collaboration has 650 scientists from 13 countries (April 2006).



TOTEM –
TOTal Elastic and diffractive cross section Measurement

Designed to measure the size of the proton and monotor the LHC luminosity.

Placed very near the beamline close to the CMS experiment.

Size: 440 m long, 5 m high and 5 m wide
Weight: 20 tonnes

In 2006, 50 scientists from 8 countries worked on TOTEM.

LHCf – Large Hadron Collider forward

Will use the particles produced in the collisions close to the beamline to simulate cosmic rays.

Located close to the beamline, 140 m to either side of the ATLAS detector.

Size: two detectors, each 30 cm long, 80 cm high, 10 cm wide
Weight: 40 kg each

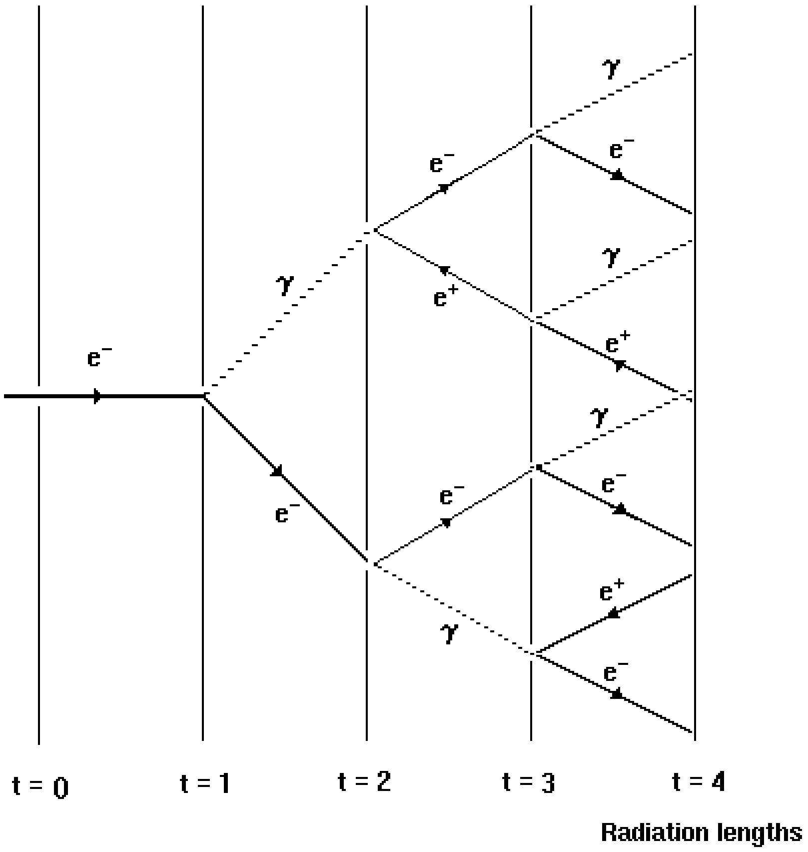
22 scientists from 10 institutes in 4 countries (September 2006).

How to detect and identify particles: principles and detector parts.

The collisions (sometimes) create new and interesting particles.
They can decay into known particles that interact in various ways with the detectors.

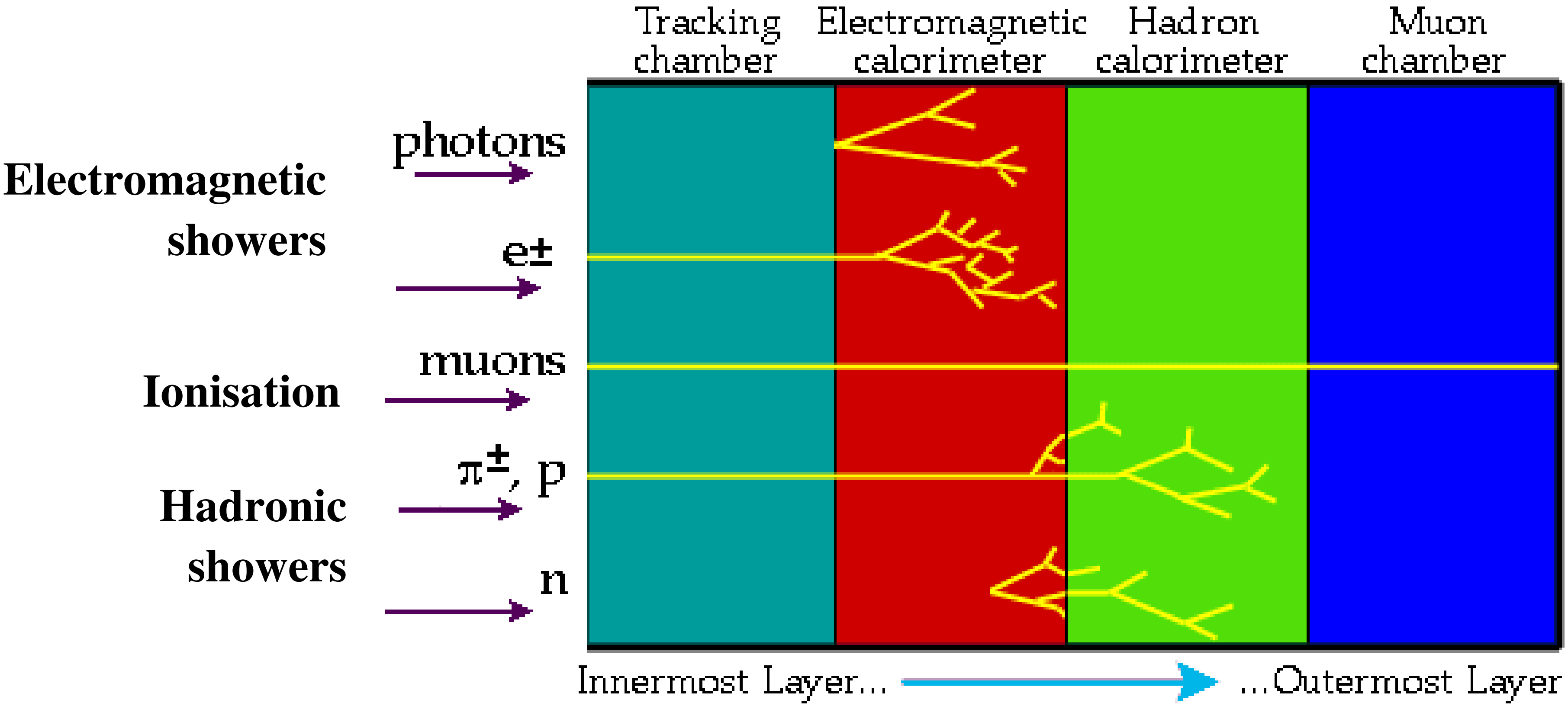
Detection: interaction with matter

- Charged particles bend in magnetic fields
  Measure momentum and charge.
- Ionization
  Charged particles ionize atoms. Leave “tracks”.
- Bremsstrahlung and pair production
  Particles (e^+/e^-) radiate photons in the interaction with the EM field from the atoms.
  Photons form e^+/e^- pairs.
  => EM energy shower.
  $dE/dx \propto 1 / m^2$ (m is the particle mass)
- Interaction with the nuclei
  Important for hadrons (stong force) and neutrinos (weak force; rare)



Detection principles

How particles react in material



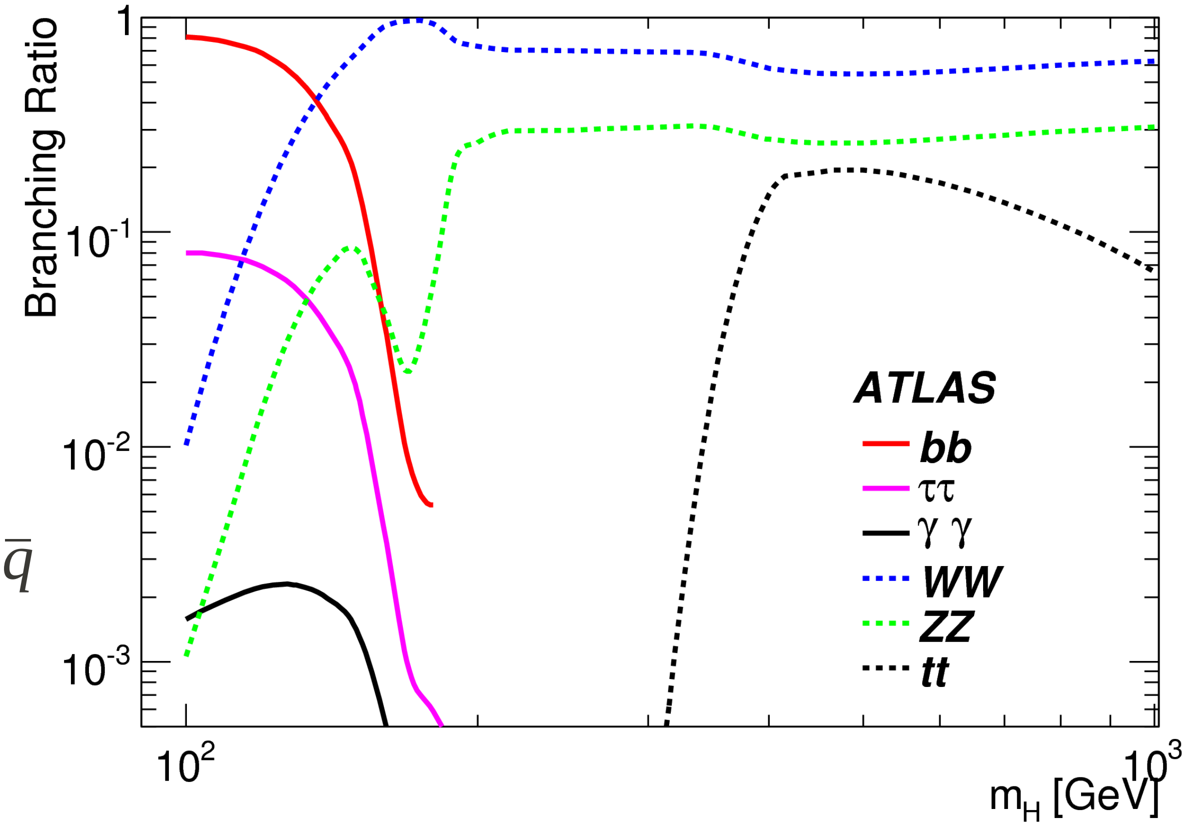
Neutrinos cannot be directly detected.

But hey, what about Higgs and top and W and Z...?

- Many particles are unstable and decay. In that case, the decay product is detected.
- “Stable” particles: e, γ, μ.
- Quarks and gluons hadronise and form **jets**
- Decays:

$$\tau^- \to e^- \bar{\nu}_e \nu_\tau,\ or\ \mu^- \bar{\nu}_\mu \nu_\tau,$$
$$or\ hadrons$$
$$W^- \to e^- \bar{\nu}_e,\ or\ \mu^- \bar{\nu}_\mu,\ or\ q'\bar{q}$$
$$Z \to e^- e^+,\ or\ \mu^- \mu^+,\ or\ q\bar{q}$$
$$t \to W^+ b$$

Figure from CERN-OPEN-2008-020



The layers of ATLAS

as an example of a detector. Most HEP detectors are very similar

Tracking:

Inner detector

Electromagnetic calorimeter

Hadronic calorimeter

Muon system

Magnets

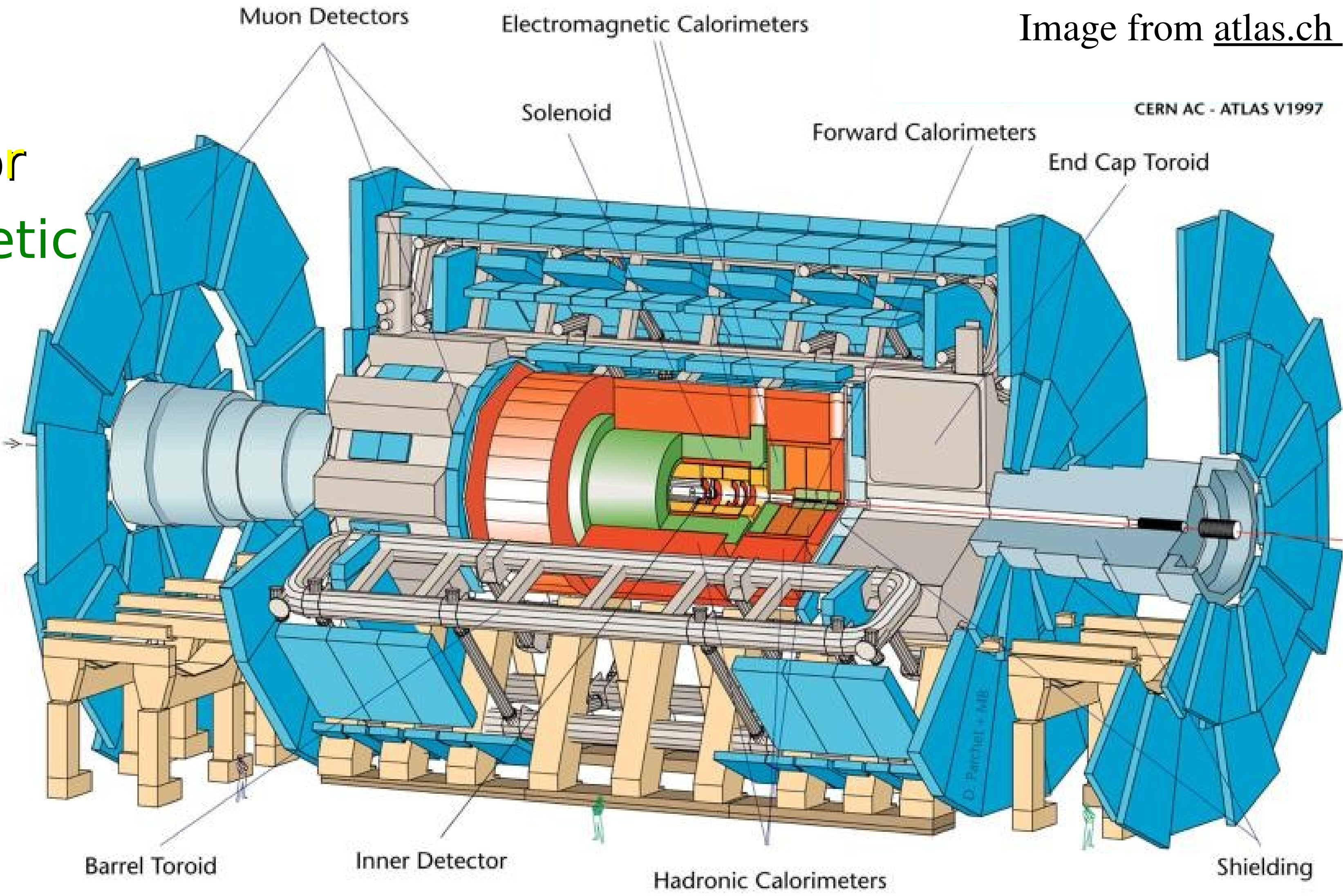


Image from atlas.ch

The ATLAS inner detector

- Charged particles leave tracks.
- A solenoid magnet: measure particle charge.
- Measure particle momenta.
- Follow the tracks to the origin: see the interaction point (vertex).

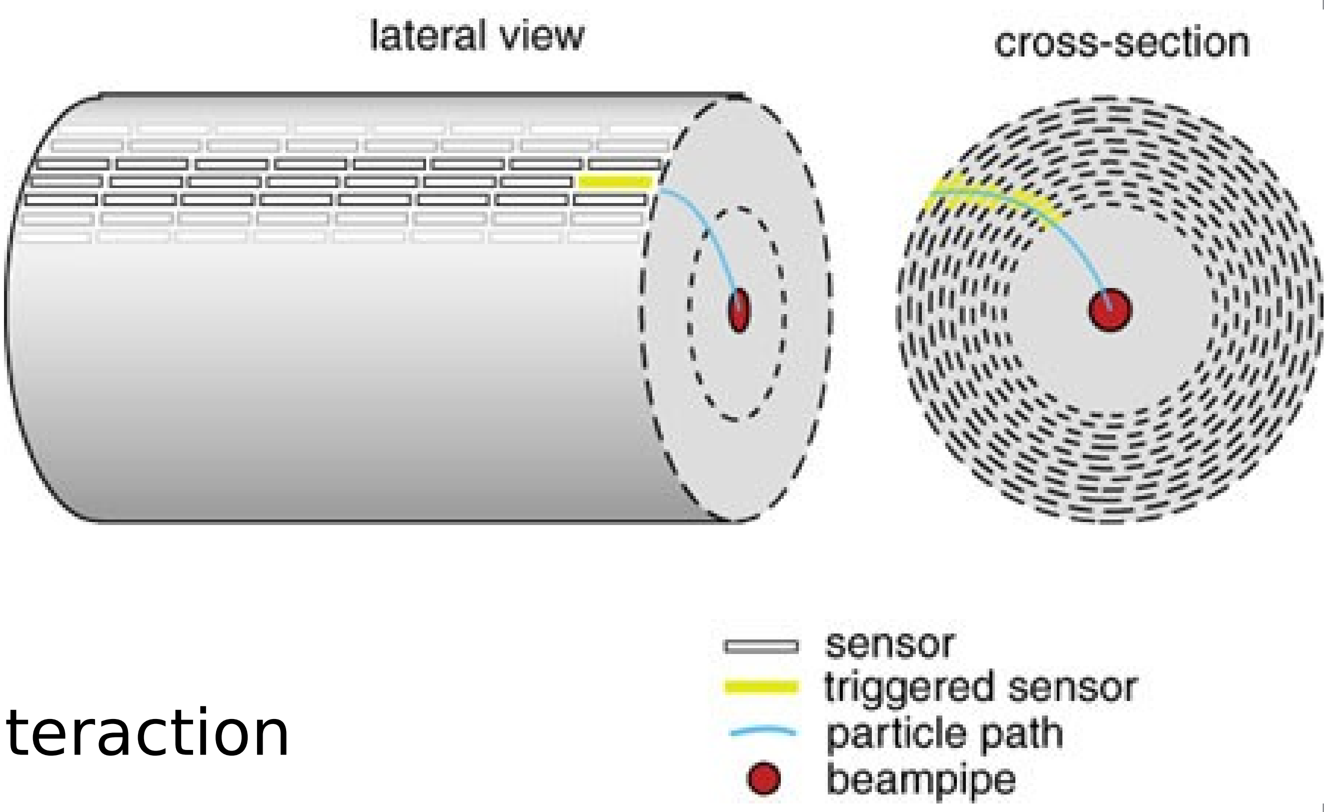


Image from www.atlas.ch

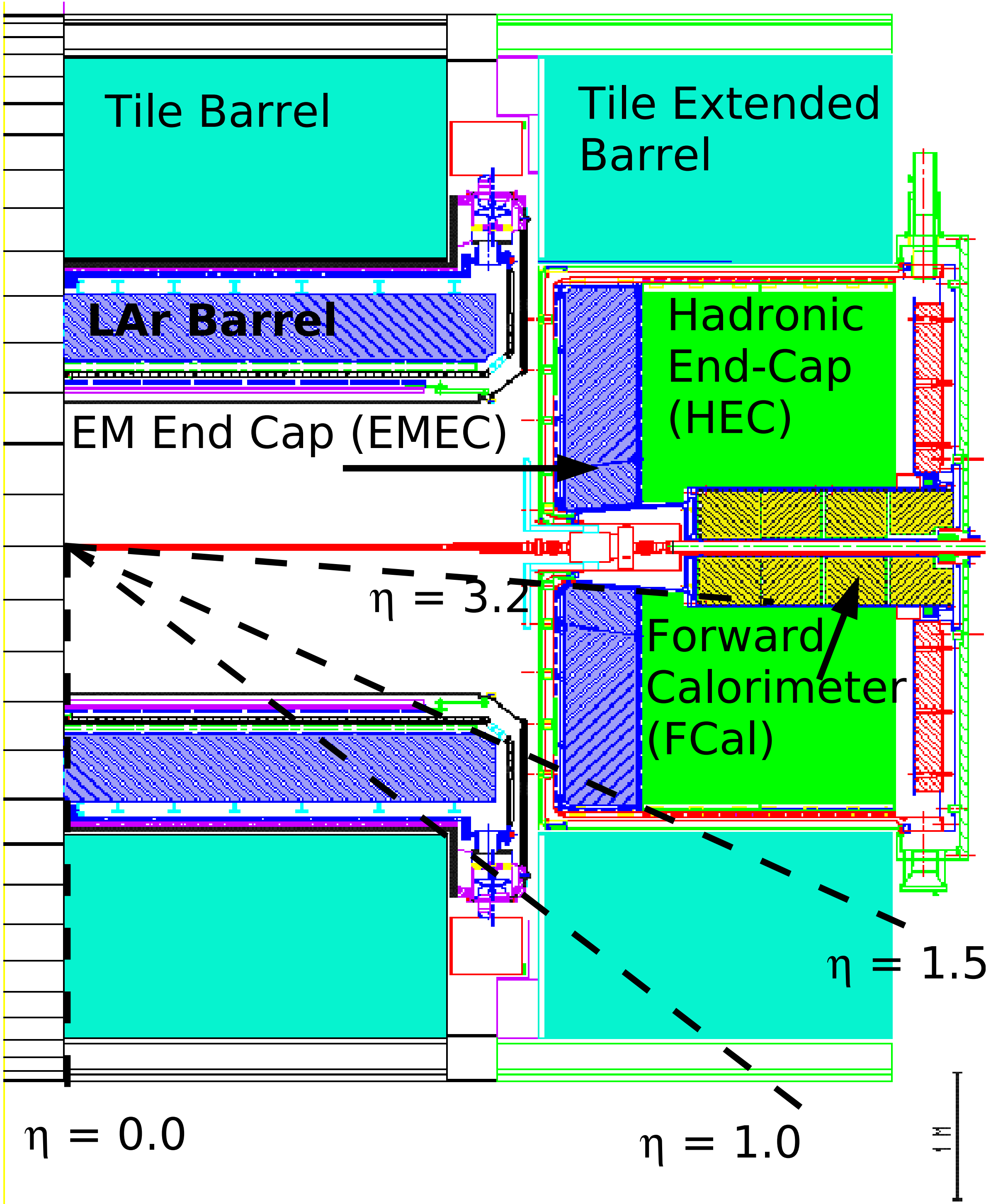
The calorimeters

Calorimeters measure **energy**. Through the total absorption of particles.

- e^+/e^- and γ cause electromagnetic showers. (Mostly) contained in the EM calorimeters.

- Hadrons cause hadronic showers. More wide-spread, propagate to the hadron calorimeter.

- Calorimeters can detect some neutral particles (e.g. neutrons).



Muon system

- The outermost ATLAS layers.
- Of all the known particles, almost only muons (and neutrinos) can escape the hadronic calorimeter.
- The muon system is a giant spectrometer that measure the momentum of the muons.
- Toroid magnets create a magnetic field for the momentum measurement.

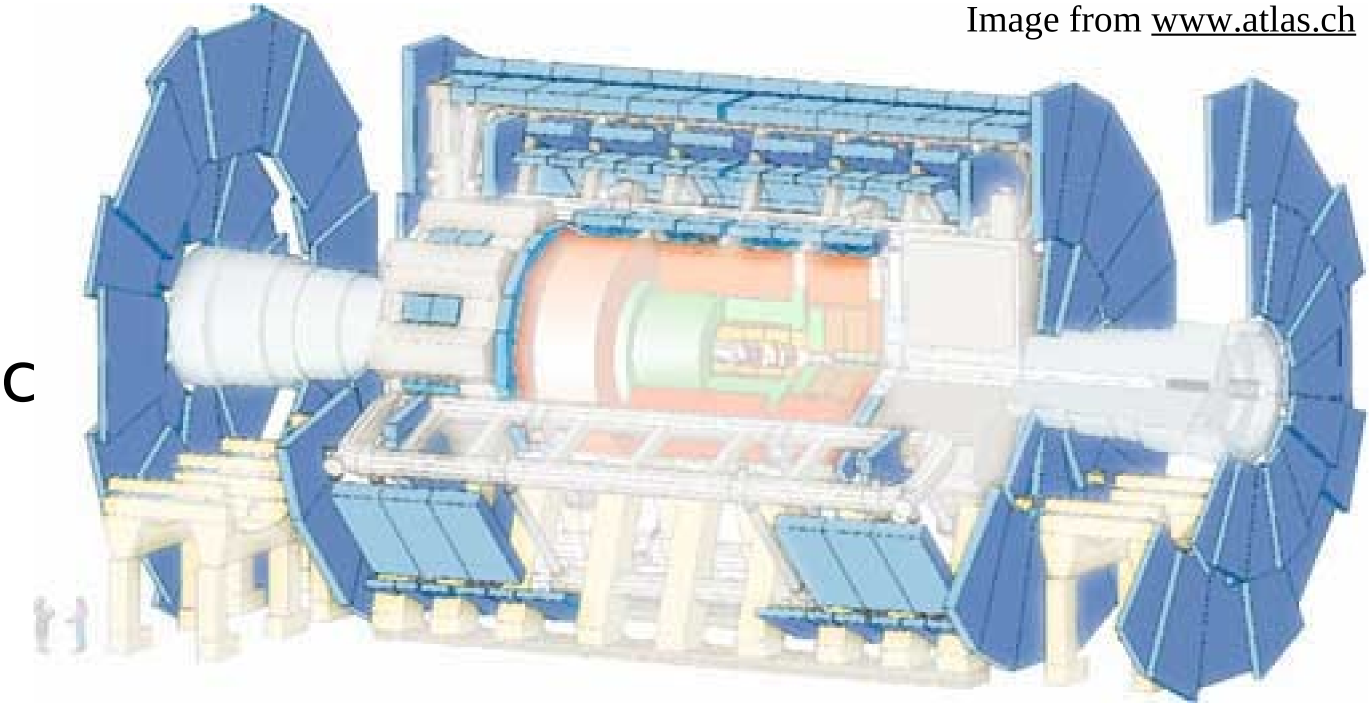


Image from www.atlas.ch

Rejecting data: the trigger system

- When LHC operates at full speed, there will be 40 million proton-proton collisions per second.
- Most collisions in ATLAS will result in something quite uninteresting (like scattered protons; we know about that already).
- Only 200 events per second can be permanently stored on disk (1 MB/event).
- The trigger system decides which events to keep and which to permanently throw away.

If all events were kept and written to CD's, the pile would be the size of the Fernsehturm in **3 seconds**...

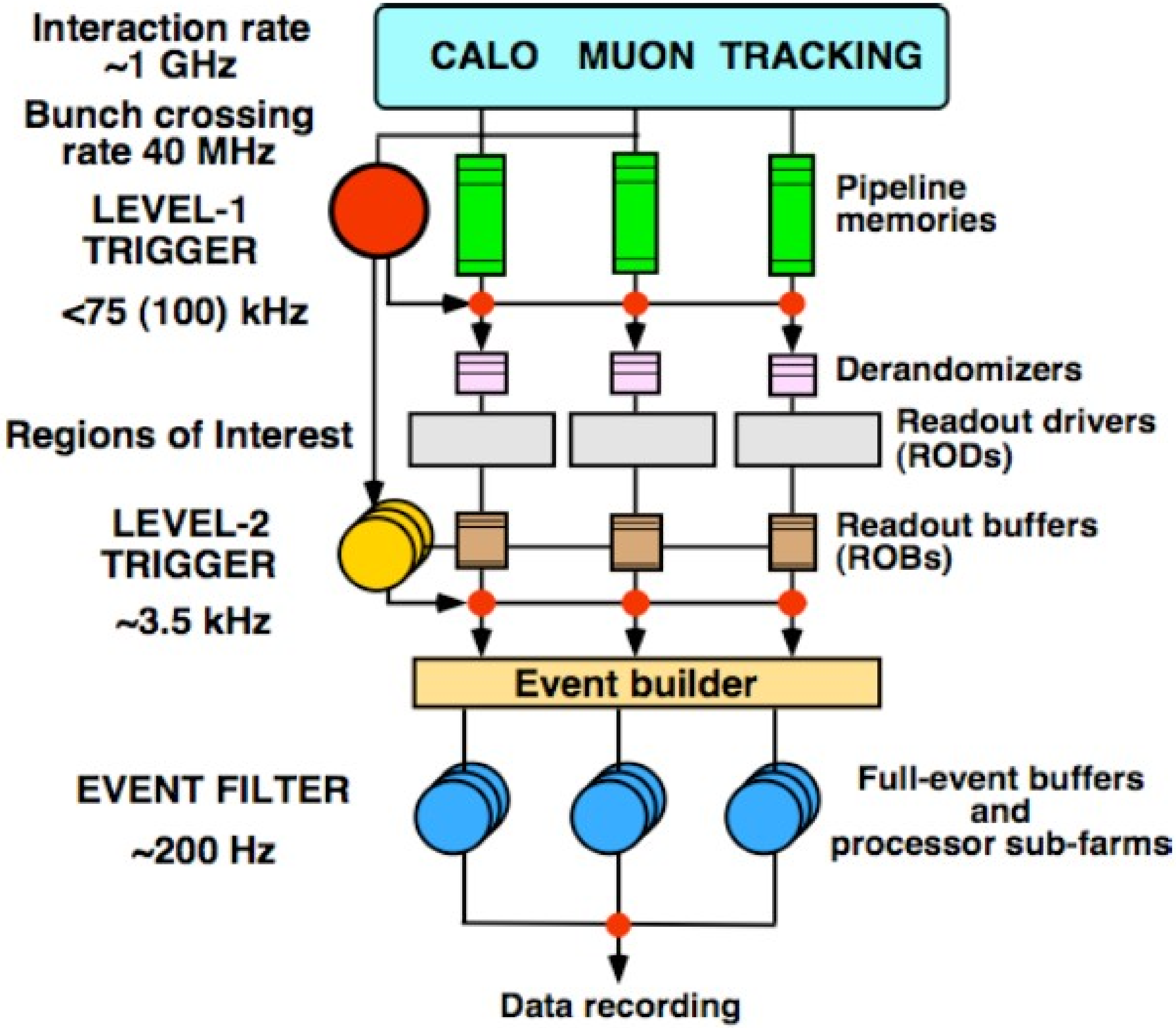
Images: wikipedia.org, confusereview.com

ATLAS trigger overview

- Keep the interesting events, remove the uninteresting (and make no mistakes!)
- Three levels:
  - Level 1 (calorimeter and muon system)
  - Level 2
  - Event filter

  } High-level trigger
- The trigger system reduces the event rate from 40 million per second to 200.

Figure from ATL-DAQ-PUB-2008-001



Summary of lecture 1

- Collider experiments are an important way of learning more about matter, forces and fundamental physics.
- The LHC is the world's largest hadron collider, with E_{CM} = 7 TeV.
- The ATLAS and CMS detectors are designed to find any new physics that the LHC may create, with many different sub-detectors for particle reconstruction and identification.
- Tomorrow: more particle identification and data analysis with ATLAS and CMS! And Higgs!

References

- Overview information about CERN, LHC and ATLAS online: http://cern.ch, http://public.web.cern.ch/public/en/LHC/LHC-en.html, http://atlas.ch
- All experimentally verified particle properties: http://pdg.lbl.gov

Comments? Questions? Anything you'd like to discuss?

Email me at elin.bergeaas.kuutmann@desy.de
or come to my office, **3L/36**.