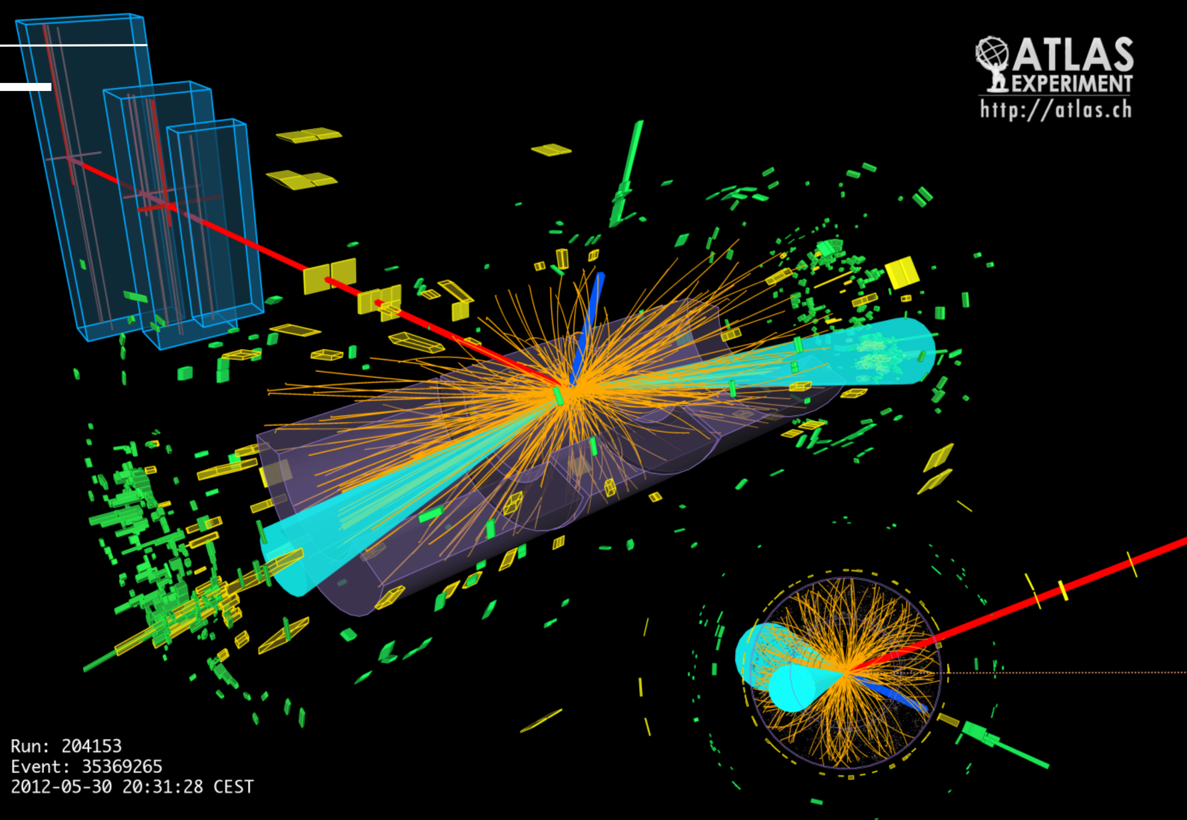
Experiments in Particle Physics: The LHC and the ATLAS



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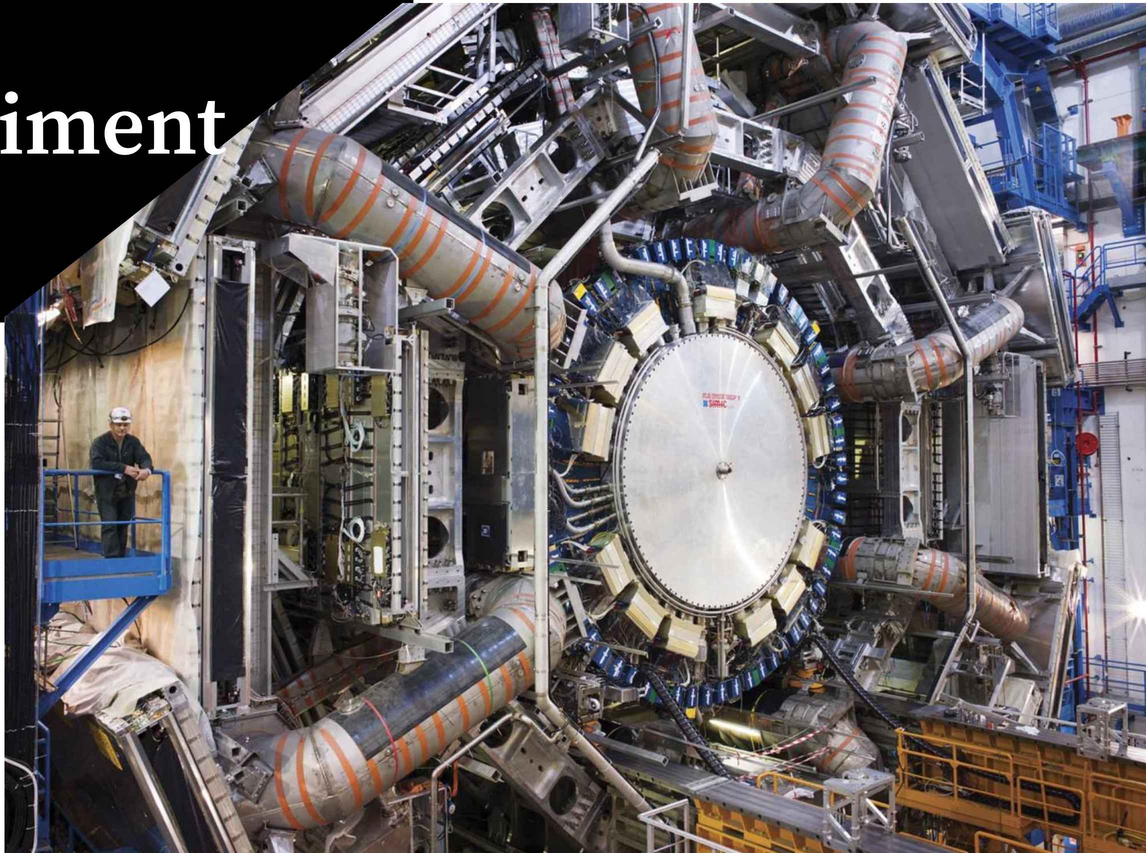
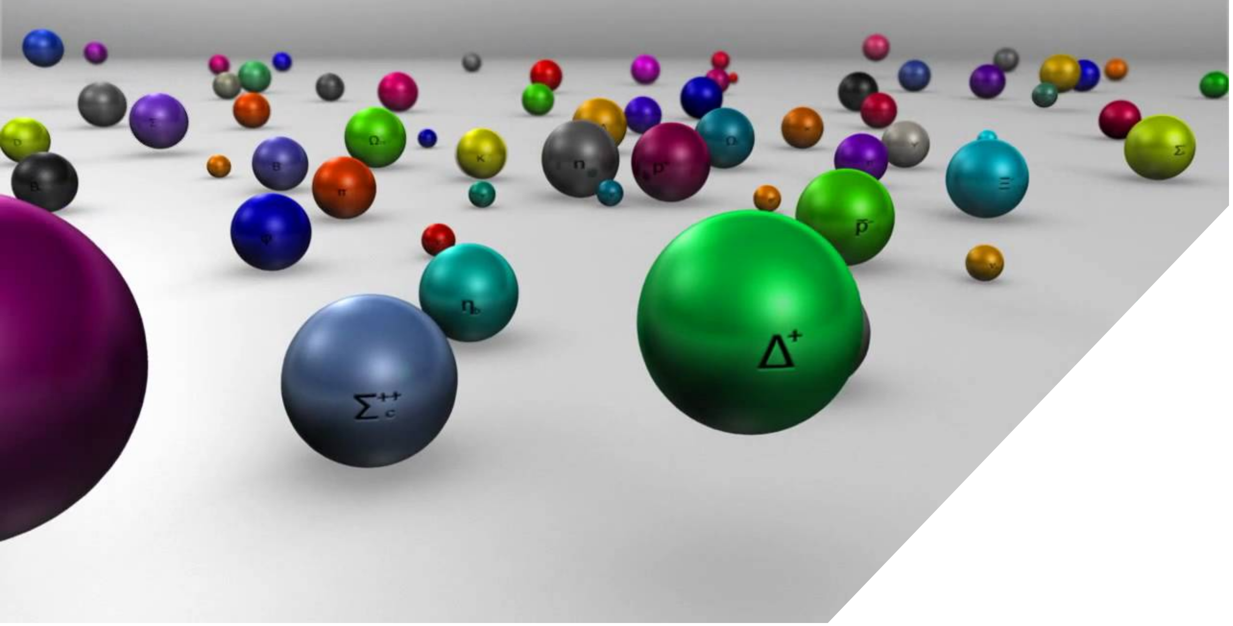
Outline

- Introduction
- Standard Model
- Experiments
- LHC and ATLAS experiment





Introduction

- *What is Physics?*
- *Model building*
- *What is Matter?*

What is Physics?

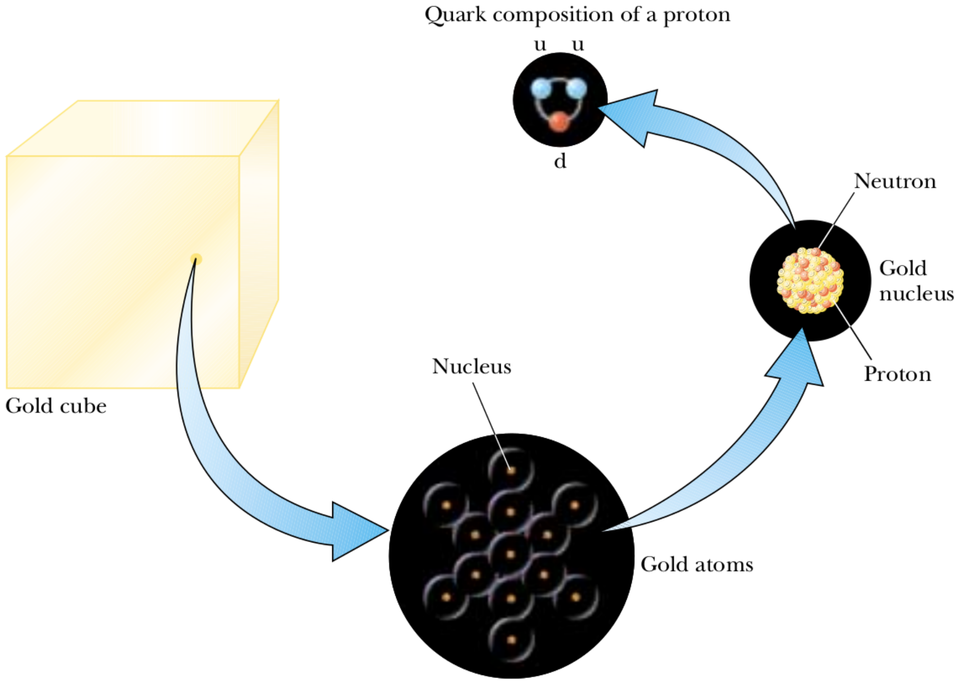
- Physics is about the **properties of natural objects**
- Physics is an **experimental** science
- Physics is about **measurable quantities**, and mathematics is the language of physics
- In physics we try to find relationships between measured quantities in terms of mathematical equations – **Physical Laws**
- Physical laws can be used to **predict** the properties of a physical object

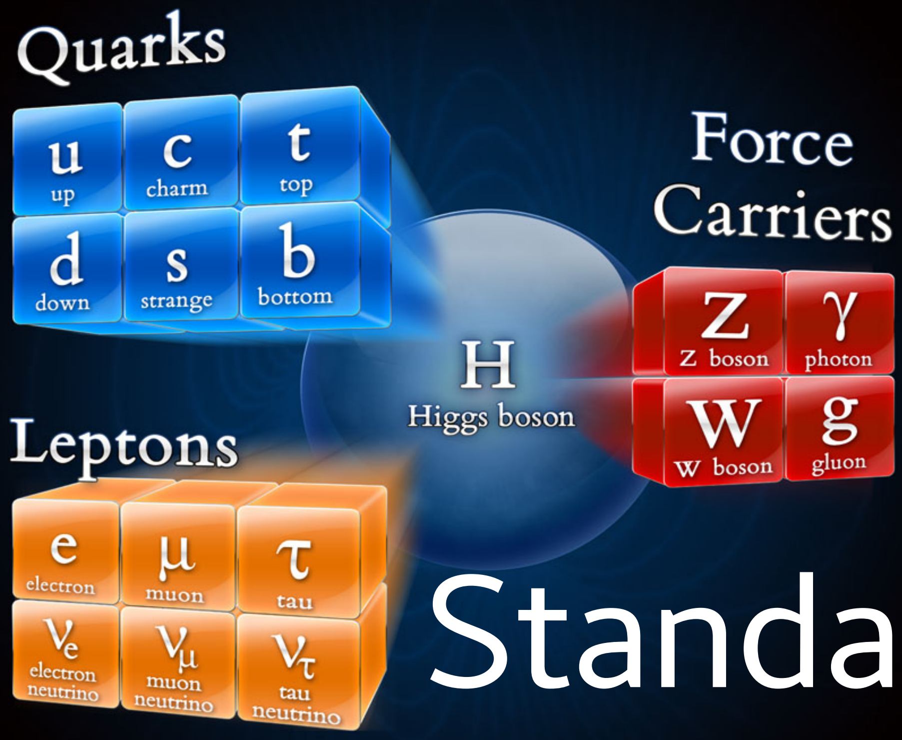
Model building

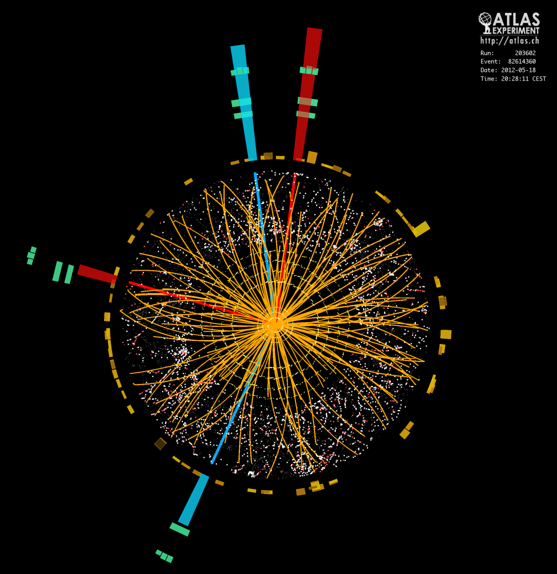
- If physicists cannot interact with some phenomenon directly, they often imagine a **model** for a physical system that is related to the phenomenon
- **Model** is a system of physical components
- Make predictions of the behavior of the system based on the interactions among the components of the system and/or the interaction between the system and its surrounding environment

What is Matter?

- Need to build a model of the matter
- Early Greek philosophers were thinking that the cutting of the matter ultimately must end when it produces a particle that can no longer be cut → matter is built with *atoms*
- In Greek, *atom* means "not sliceable"



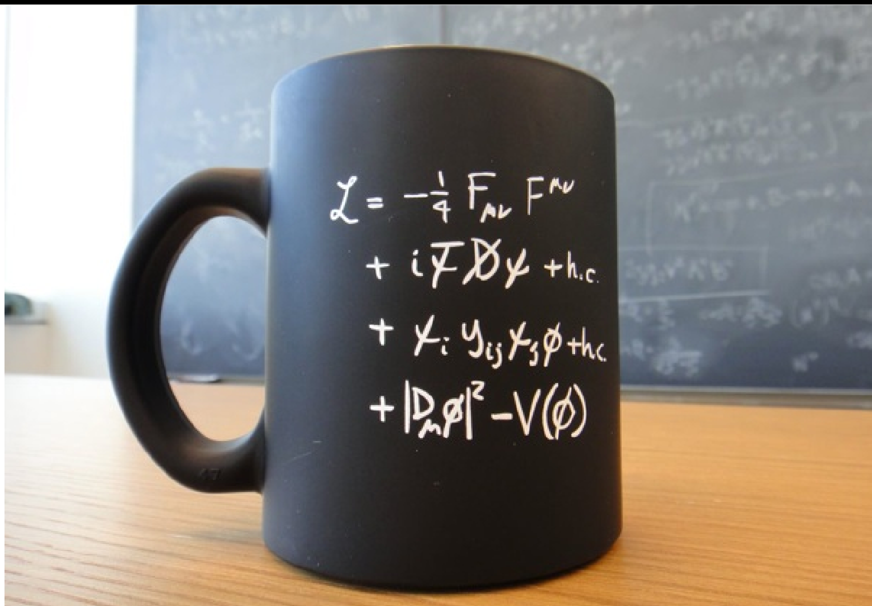




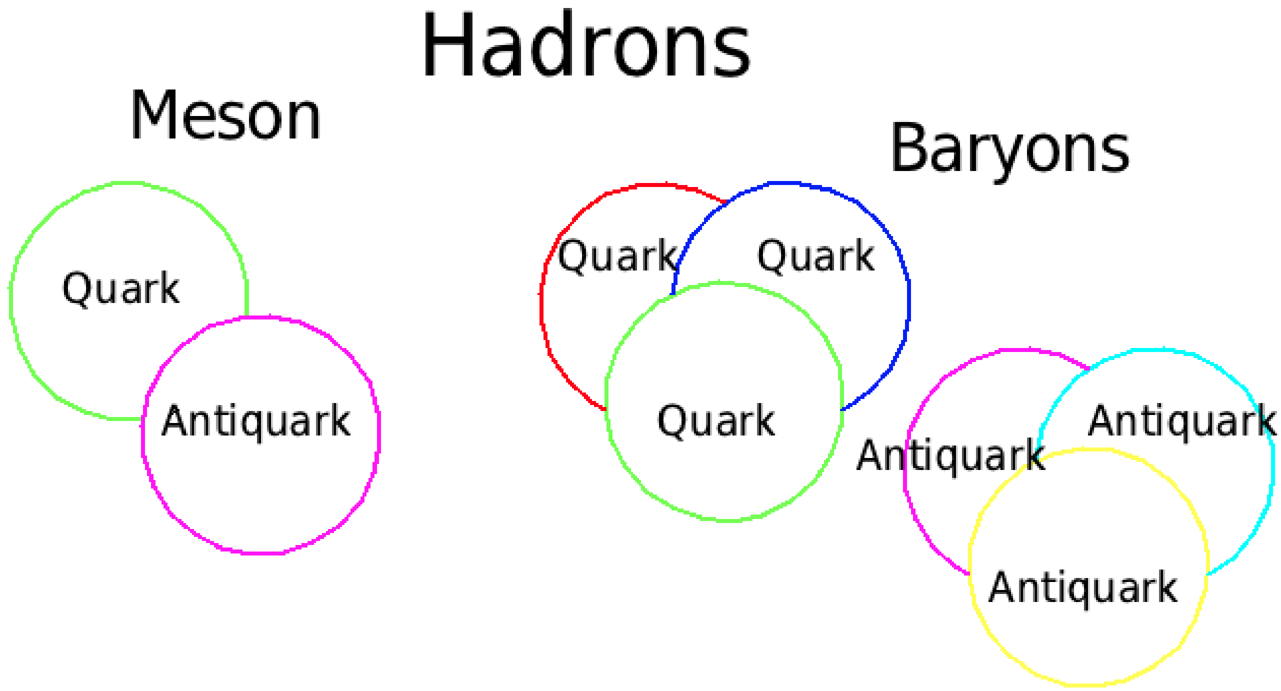
Standard Model

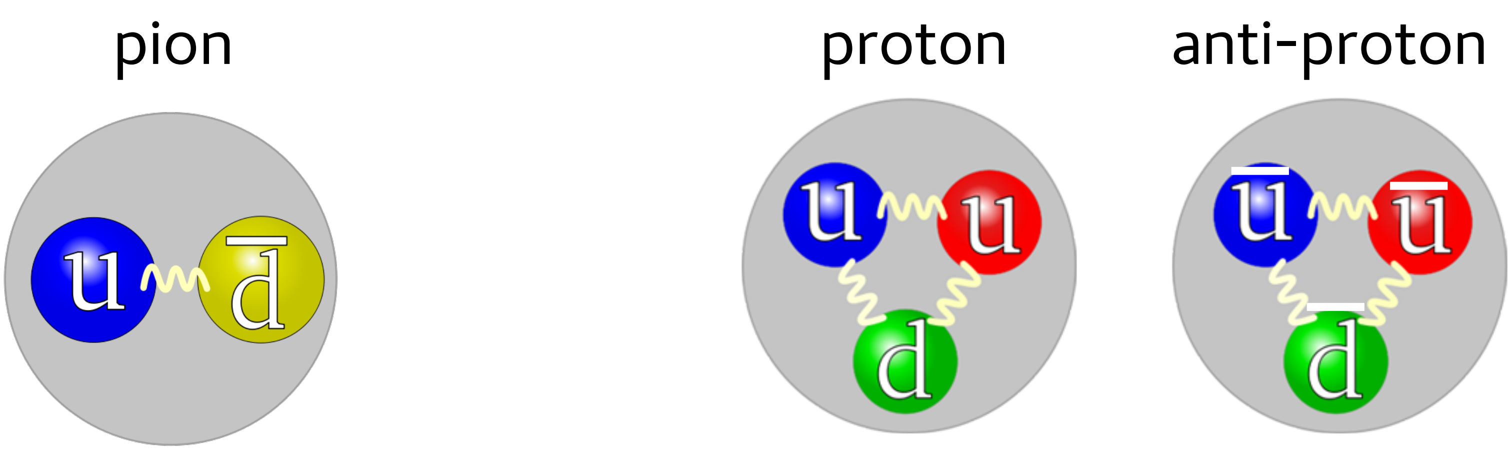
Standard Model (SM)

- *Quantum field theory based on lagrangians*
- *Describes elementary blocks of the matter and fundamental forces*
- *We use the SM to predict experimental observations*



- ***Leptons*** *do not form a composite particle (no binding between them)*
- *Quarks do not exist in a free state*
- *They are held together by the strong force in a* ***hadron***





Energy and mass

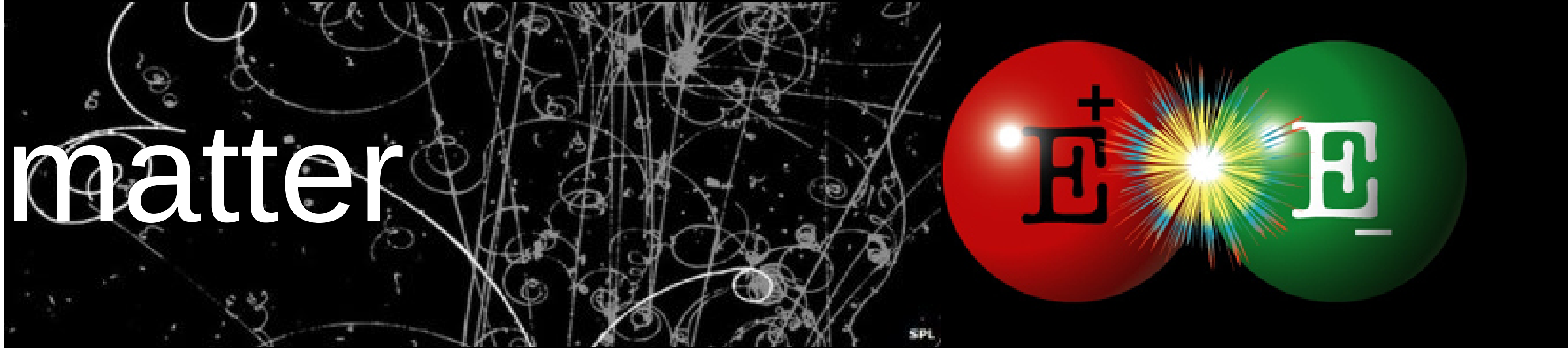
$E=mc^2$

Energy and mass in Particle Physics

- *Energy and mass are two sides of the same coin.*
- *Mass can transform into energy and vice versa in accordance with Einstein's famous equation ($E=mc^2$).*
- *Also, because of this equivalence, mass and energy can be measured with the same unit (by setting c=1).*
- *At the scale of particle physics these are the* ***electronvolt*** *(eV) and its derivatives keV (10^3 eV), MeV (10^6 eV), GeV (10^9 eV) and TeV (10^{12} eV)*

> *The definition of the electronvolt comes from the simple insight that a single electron accelerated by a potential difference of 1 volt will have a discrete amount of energy (measured in joules), E=qV where q is the charge on the electron in coulombs and V is the potential difference in volts. Hence 1 eV = (1.602×10^{-19} C) x (1 V) = 1.602×10^{-19} J.*

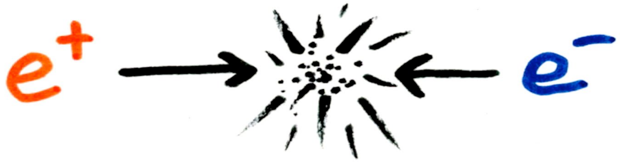
Antimatter



Einstein's equation of motion*: $E^2 = p^2c^2 + m^2c^4$

Two energy solutions for the same mass;

- Matter
- Antimatter

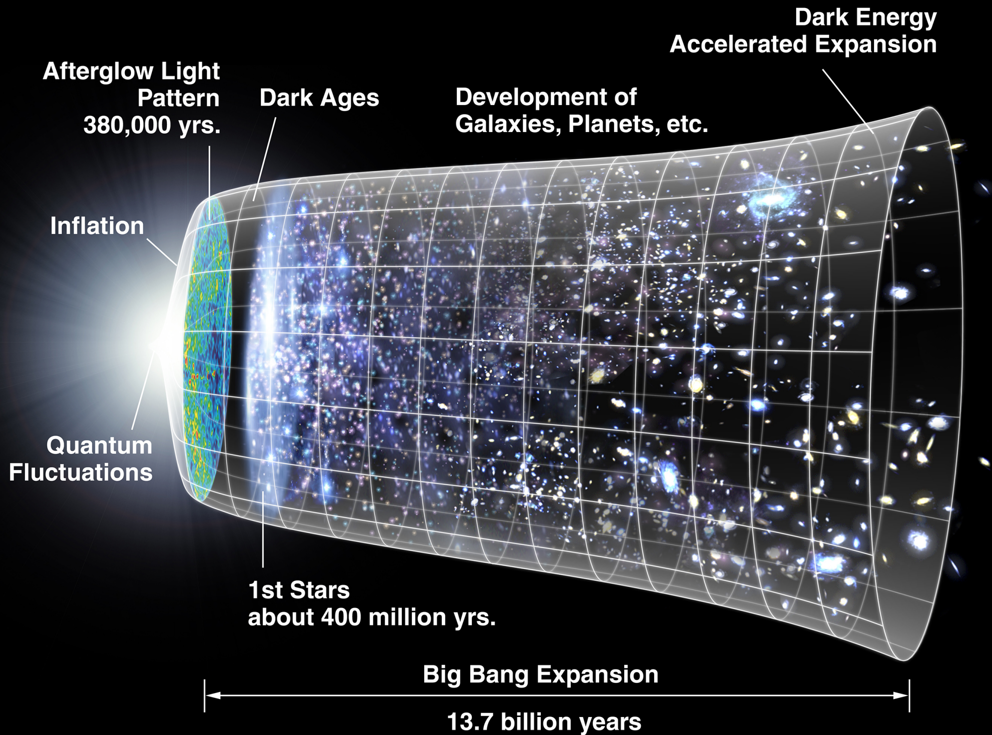


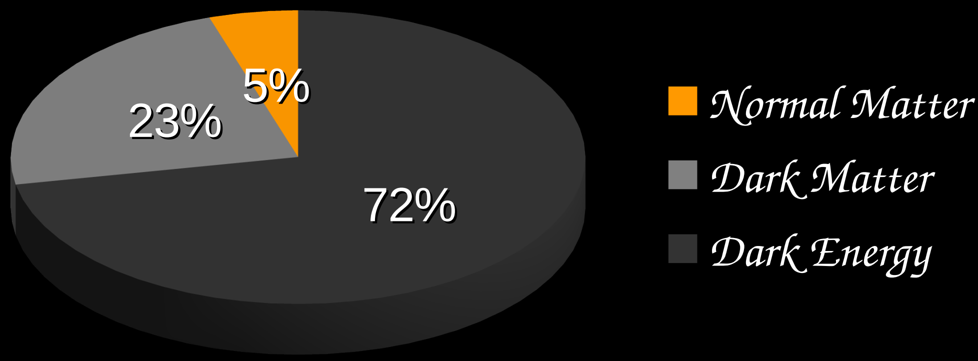
Every fermion has an antimatter version.

Same mass, opposite charge

eg. antiquark $\bar{q}$, antimuon μ^+, antineutrino $\bar{\nu}$

*(and others, more famously Dirac)

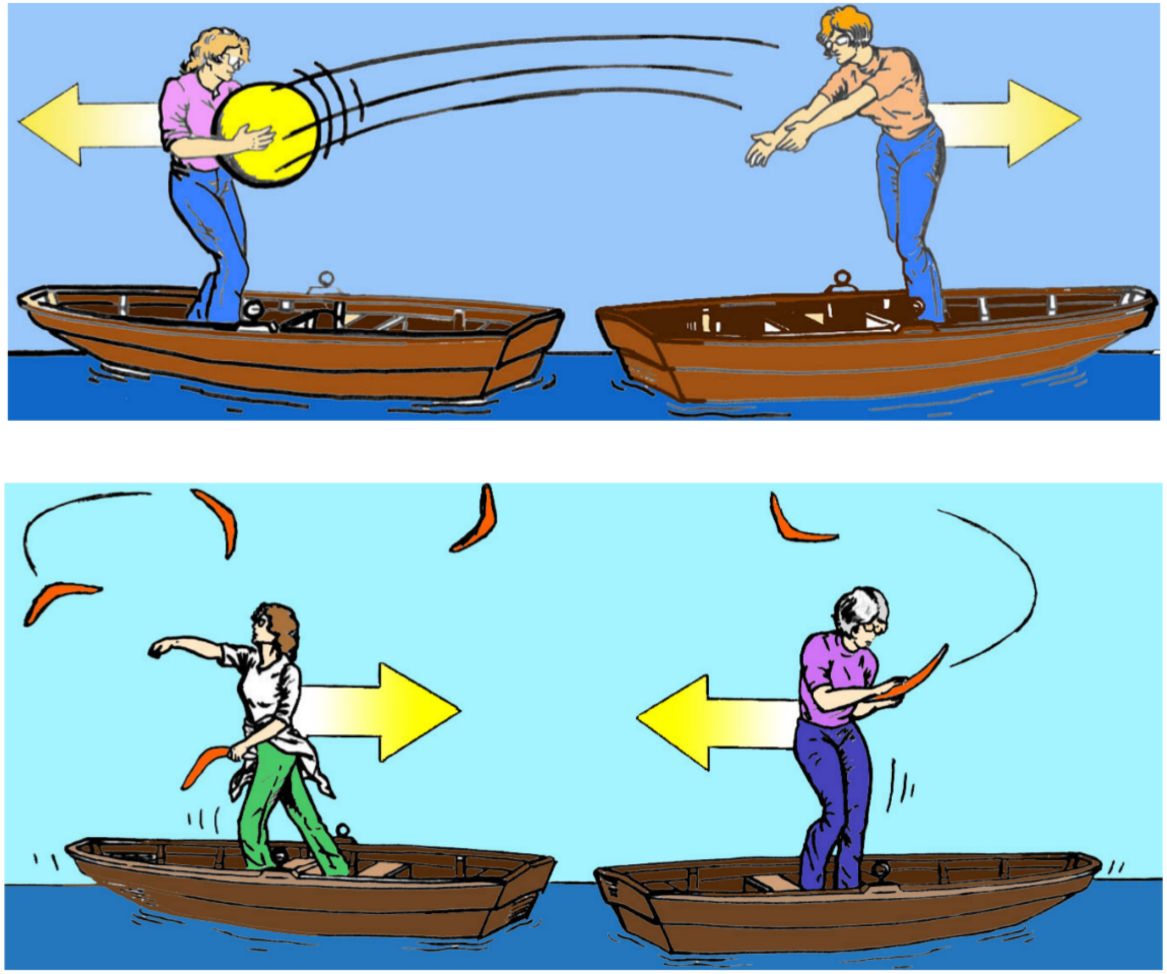




- *Matter and antimatter particles are always produced as a pair*
- *The Big Bang should have created equal amounts of matter and antimatter in the early universe*
- *Everything we see from the smallest life forms on Earth to the largest stellar objects is made almost entirely of matter*
- *Comparatively, there is not much antimatter to be found*
- *One of the greatest challenges in physics is to figure out what happened to the antimatter, or why we see an asymmetry between matter and antimatter*

Matter is held together by forces;

– mediated by force carrying particles (bosons; spin 1)



Forces

Electromagnetic

0 eV/c²

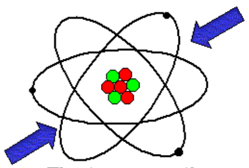
0

1

γ

photon

U(1)



Electromagnetic force binds atoms

Strong (QCD)

8 x

0 eV/c²

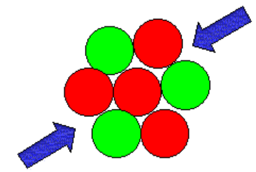
0

1

g

gluon

SU(3)



Strong force binds the nucleus

Weak

2 x

80.4 GeV/c²

±1

1

W

W boson ,

91.2 GeV/c²

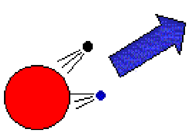
0

1

Z

Z boson

SU(2)



Weak force in radioactive decay

Note:
No gravity!!

Successes

Consistent with experiment

No deviations seen

Predictions (eg Higgs) proven

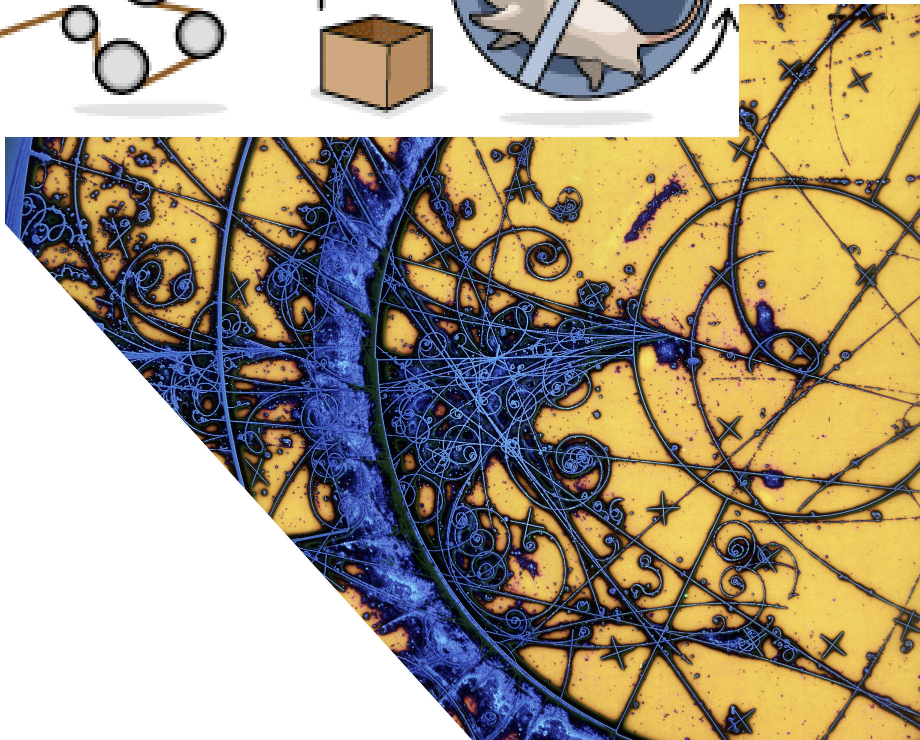
Holes

Incomplete (eg. no gravity)

Few explanations

Many ad-hoc additions to fit experimental data

Need to find a breakdown to move forward.
Need experiments.

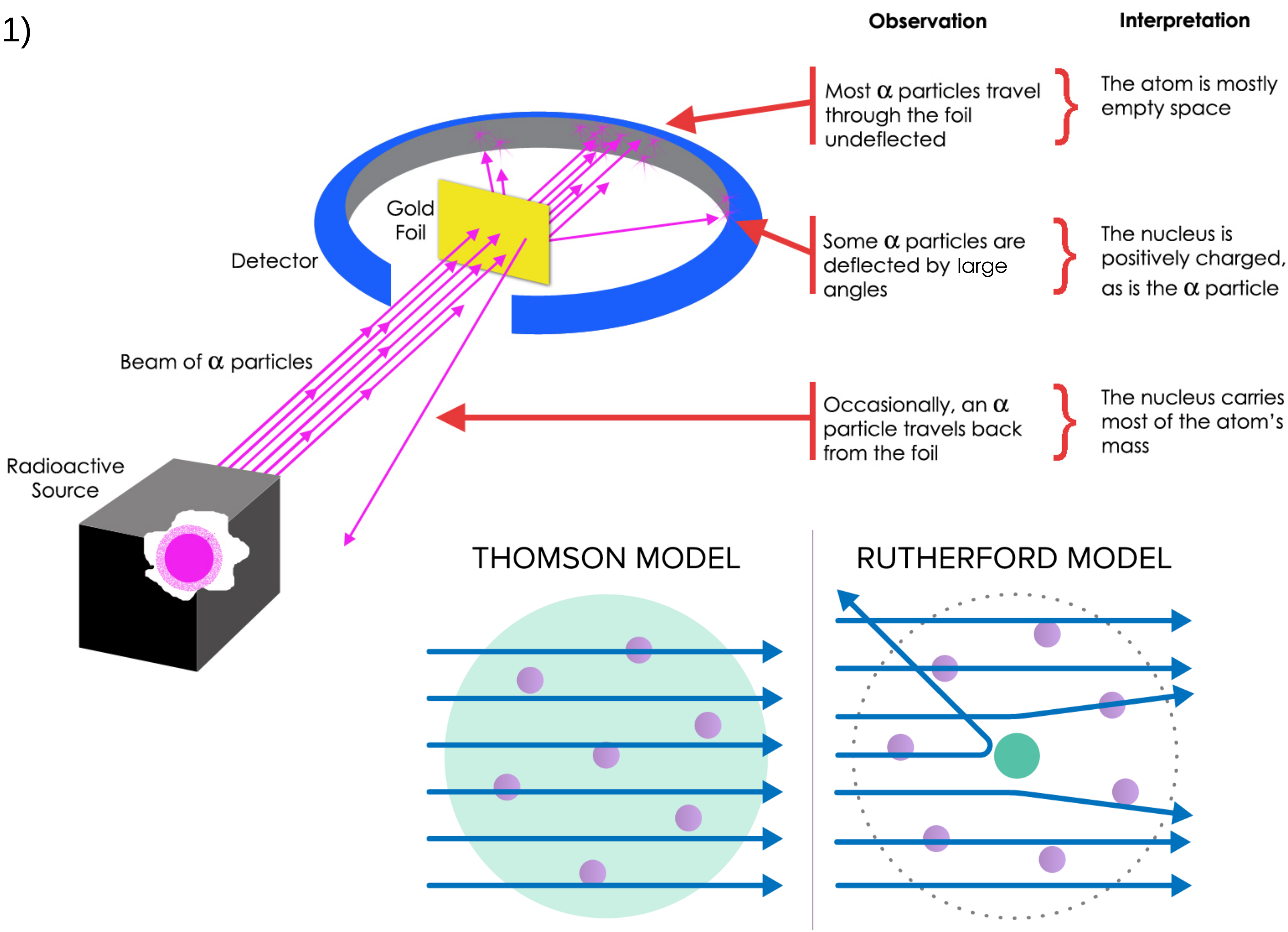


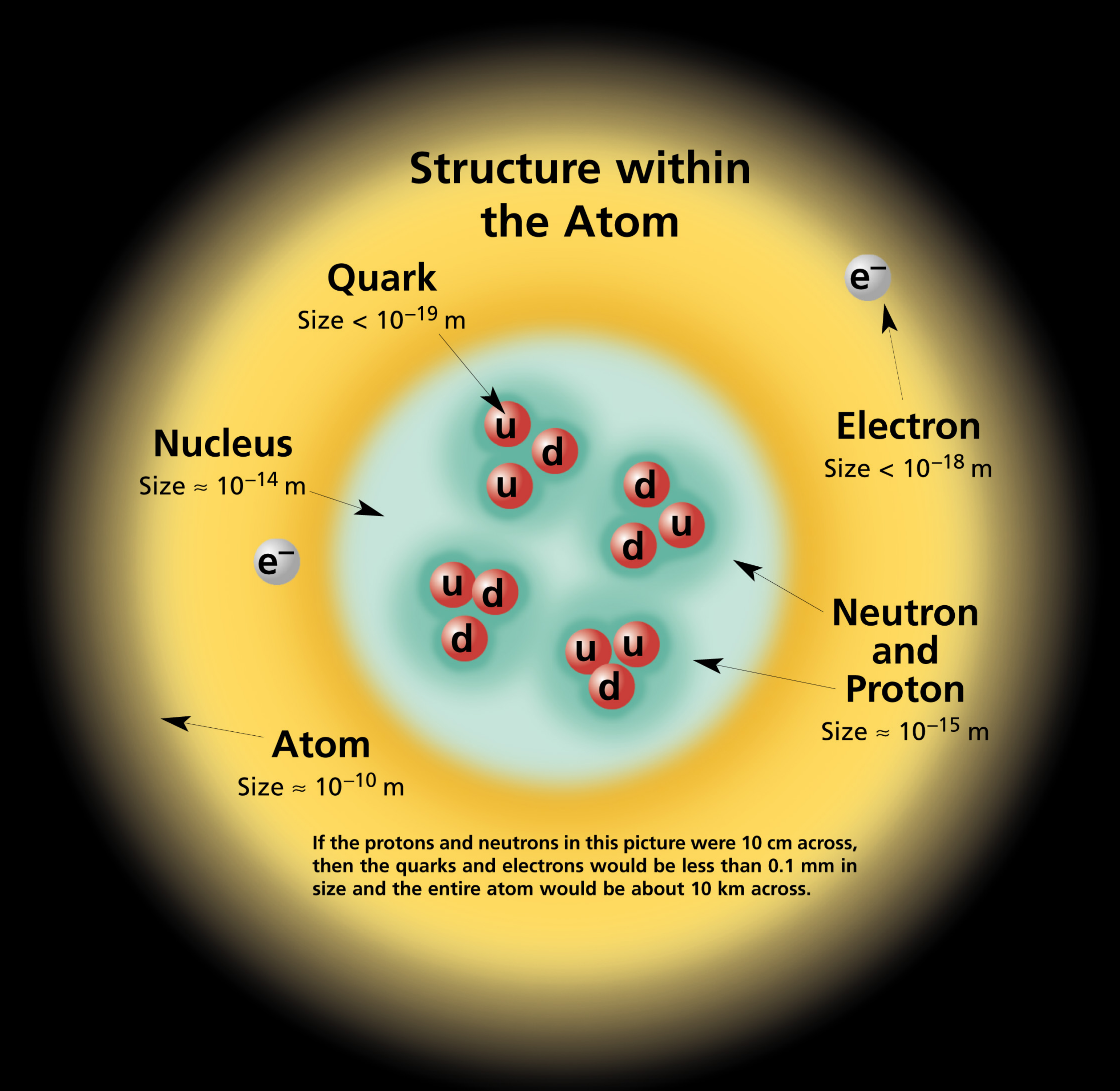
Do experiments to

- *explore the nature*
- *test your prediction*
- *check your imagination*
- *find new phenomenon*

Rutherford's Experiment

(1911)





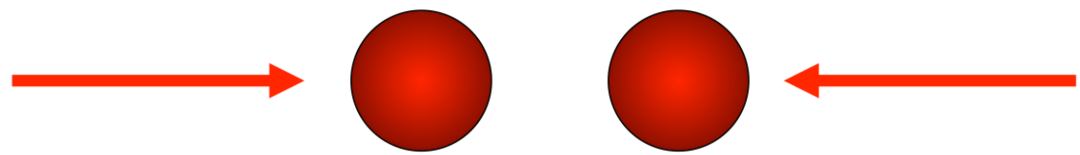
Structure within the Atom
Quark
Size < 10^{-19} m
e^-
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
u
d
u
d
d
u
u
d
Electron
Size < 10^{-18} m
e^-
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Particle accelerators

Need a particle accelerator to

- *produce high mass particles*
- *study processes at high energies*
- *study processes at small distances*

Beams of charged particles accelerated by electromagnetic force*.



Centre of mass energy: $\sqrt{s} = \sqrt{\left(\sum_i E_i^2 - \sum_i p_i^2\right)}$

If a proton with 7 TeV energy collides to a proton at rest, then at the center of mass there is only ~115 GeV energy!

DeBroglie Wavelength: $$\lambda = \frac{hc}{pc}$$ where hc = 1239.84 eV nm and pc is expressed in electron volts.

$\lambda \sim 10^{-18} m$ at TeV scale energies

Linear

No bremsstrahlung

Long (for high energy)

“one shot” accelerator

Circular

Bremsstrahlung

Strong magnets needed to maintain circular beam path

Long beam lifetime; many revolutions, many collisions.

Protons vs. electrons

$$d\,\vec{p}/dt = q\,\vec{E} + q\,[\vec{v}\,\vec{B}]$$

$$E_{\mathrm{kin}} = qU$$

Speed of light $c = 299\ 792\ 458$ m/s

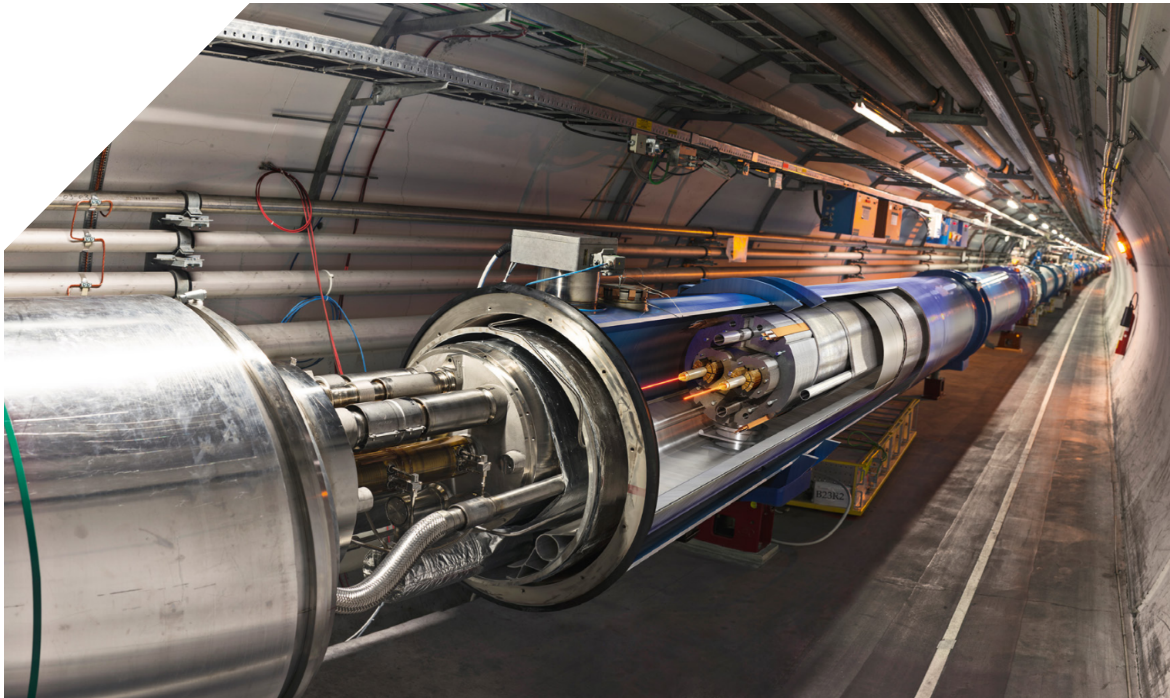
Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2

- *The Large Hadron Collider (**LHC**) is **the world's largest and most powerful particle accelerator**.*
- *The LHC consists of a 27-kilometre ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.*

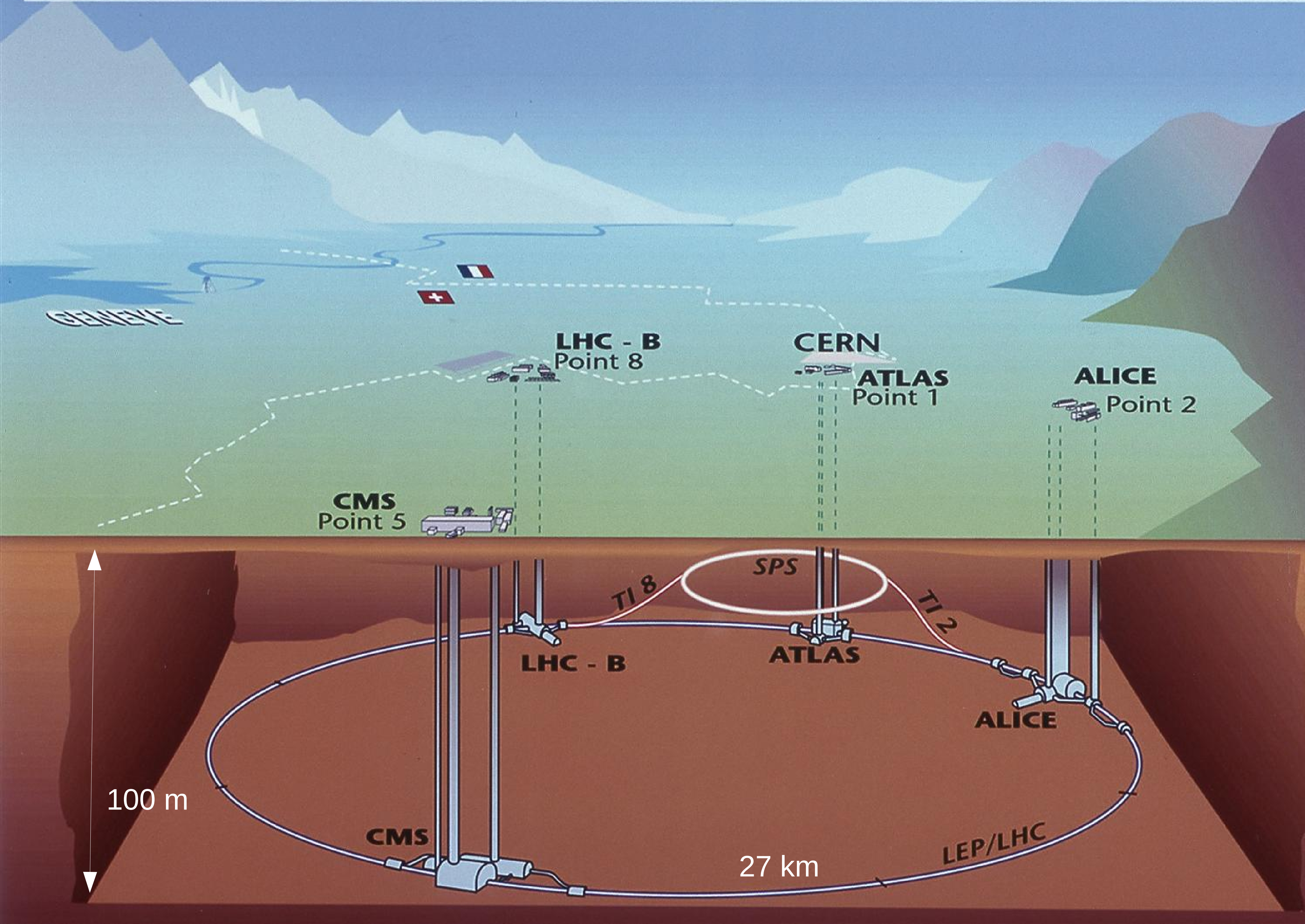
The Large Hadron Collider

- *Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide.*
- *The beams travel in opposite directions in separate beam pipes – two tubes kept at ultrahigh vacuum.*
- *The LHC designed to accelerate particle beams to the energy of 7 TeV.*

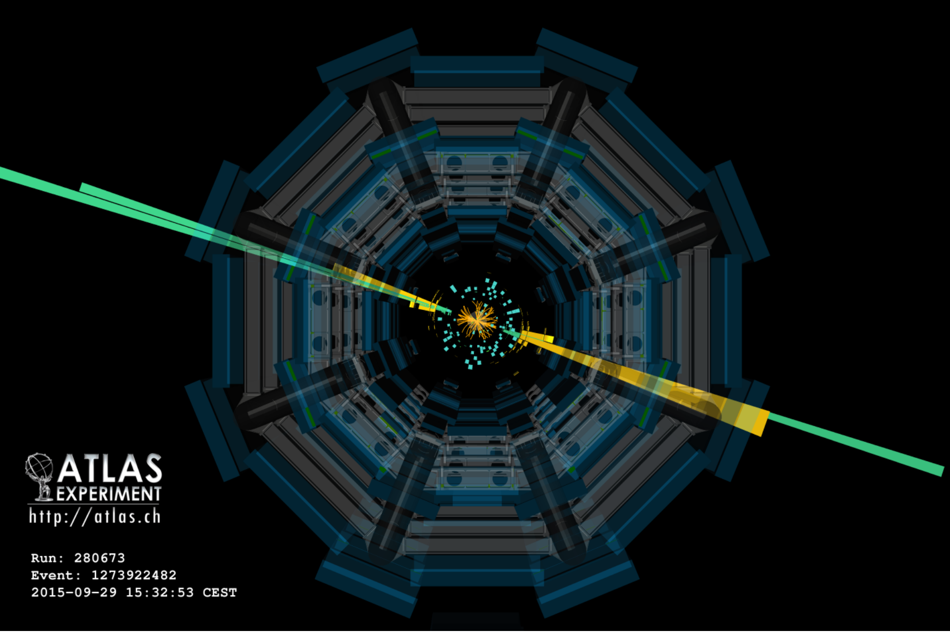



Large Hadron Collider
Lake of Genev
CMS
LHCb
ALICE
ATLAS

Overall view of the LHC experiments.



//atlas.physicsmasterclasses.org/videos/warum.mp4

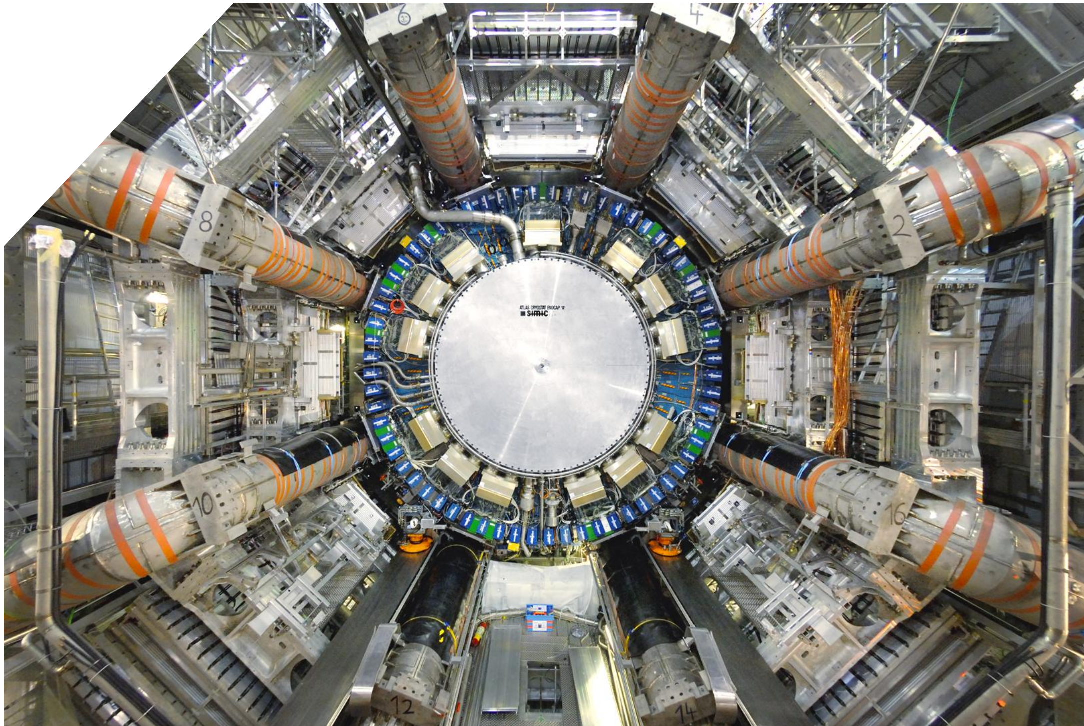


- *ATLAS is one of the four major experiments at the LHC at CERN.*
- *It is designed to exploit the full discovery potential and the huge range of physics opportunities that the LHC provides.*

The ATLAS experiment

Some of the key questions that ATLAS addresses are:

- *What are the basic building blocks of matter?*
- *What are the forces that govern their interactions?*
- *What happened to antimatter?*
- *What is "dark matter"?*
- *What was the early universe like and how will it evolve?*
- *How does gravity fit in?*



The search for the unknown

The ATLAS Collaboration

- *The ATLAS Collaboration comprises 5000 members from about 180 institutions around the world, representing 38 countries from all the world's populated continents.*
- *It is one of the largest scientific collaborative efforts ever assembled.*

Georgians in the ATLAS Collaboration:

Physicists from two institutes of Tbilisi State University

- **High Energy Physics Institute**
- **Andronikashvili Institute of Physics**

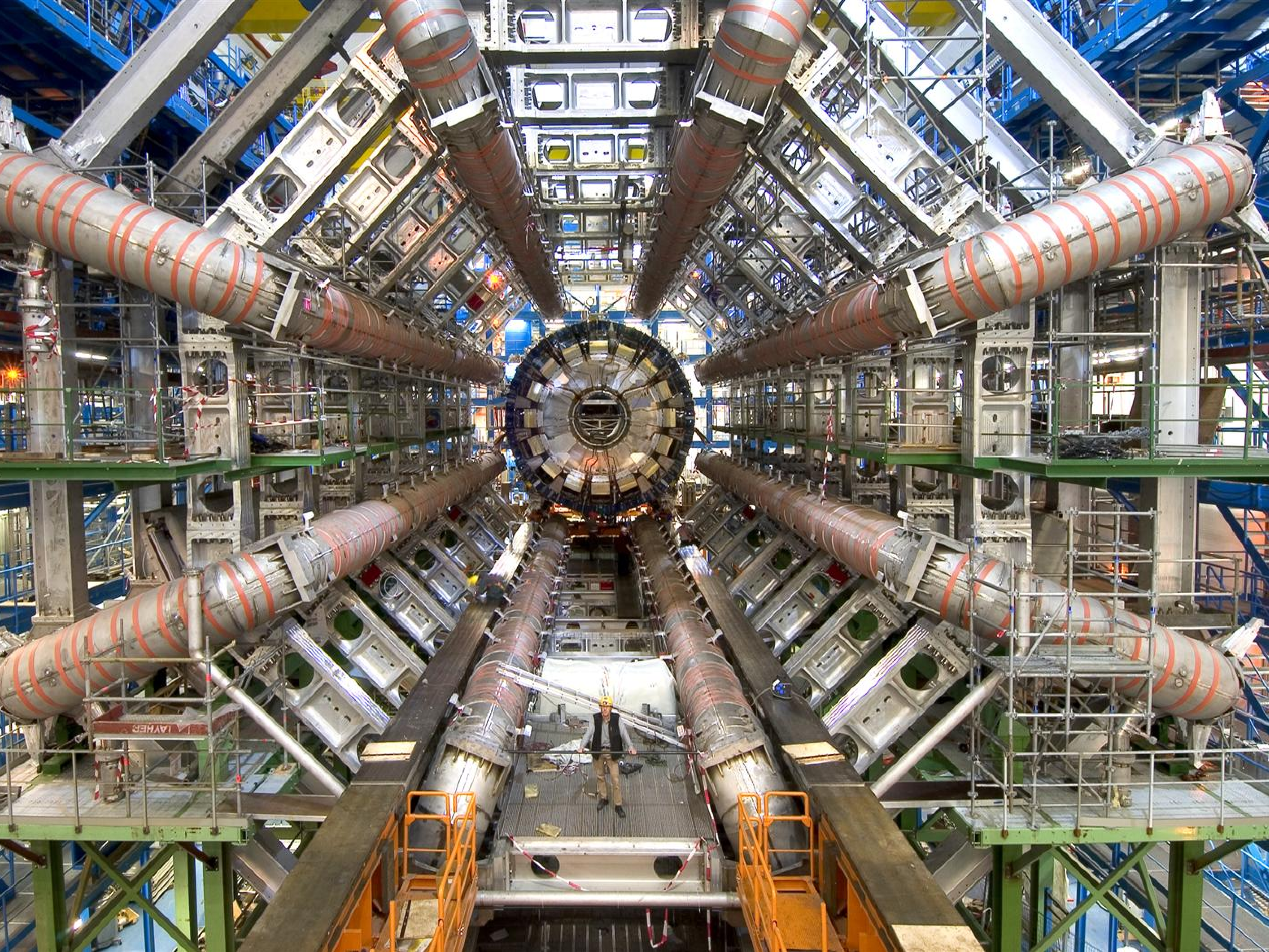
and **engineers** from

- **Georgian Technical University**

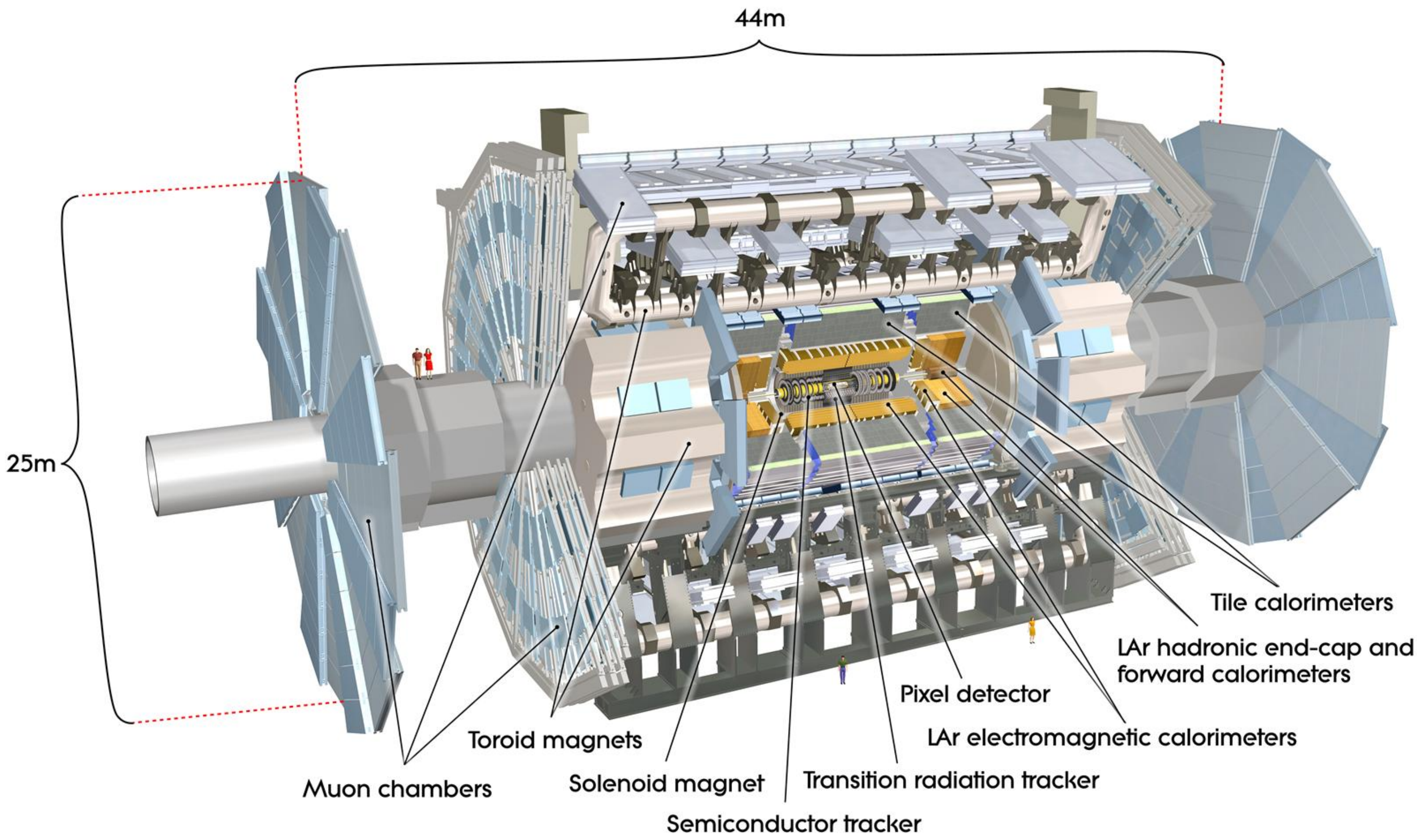
are participating at the ATLAS experiment

Physics Analysis/Detector Tasks

Detector Software Development



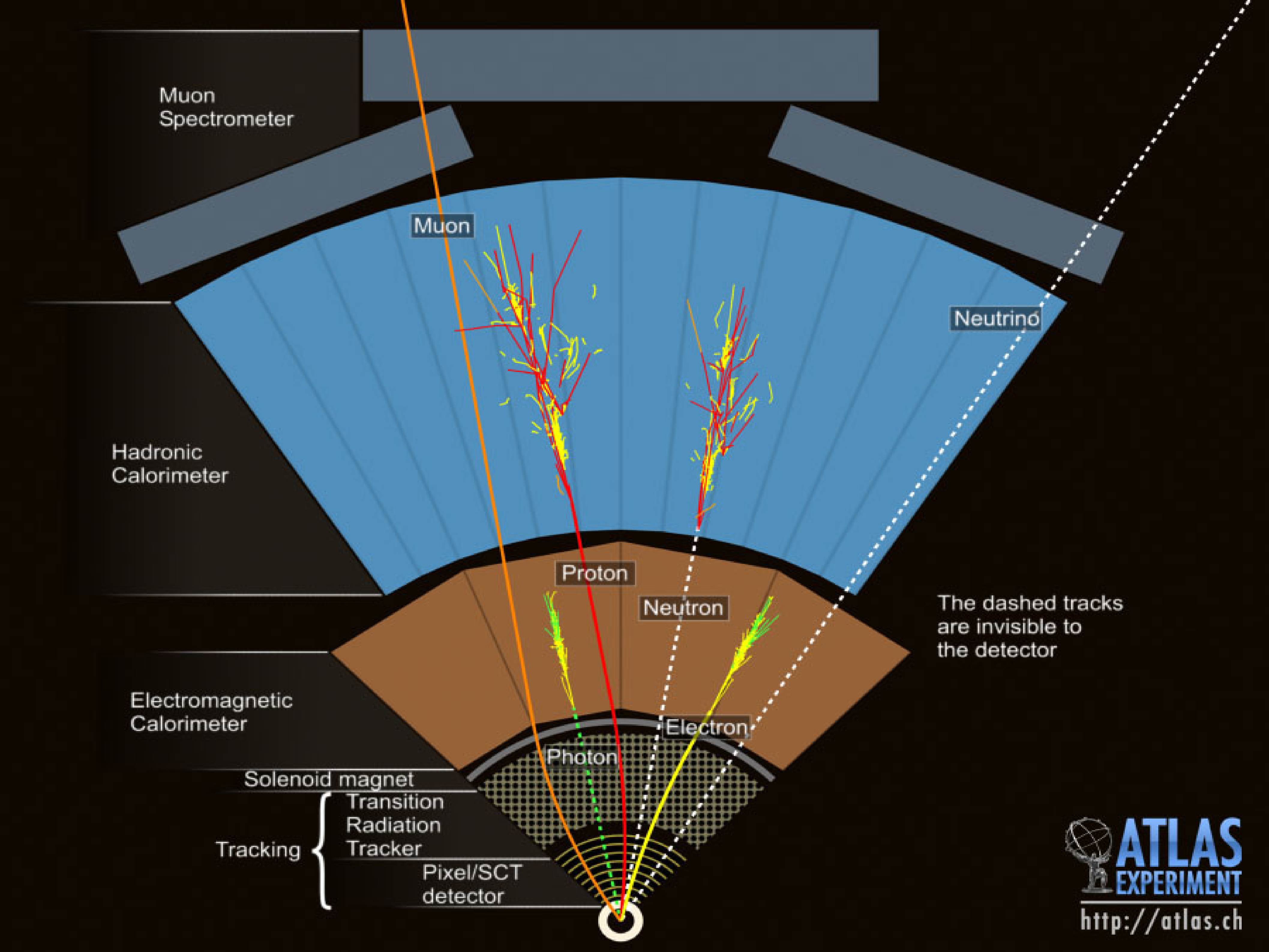
ATLAS Detector



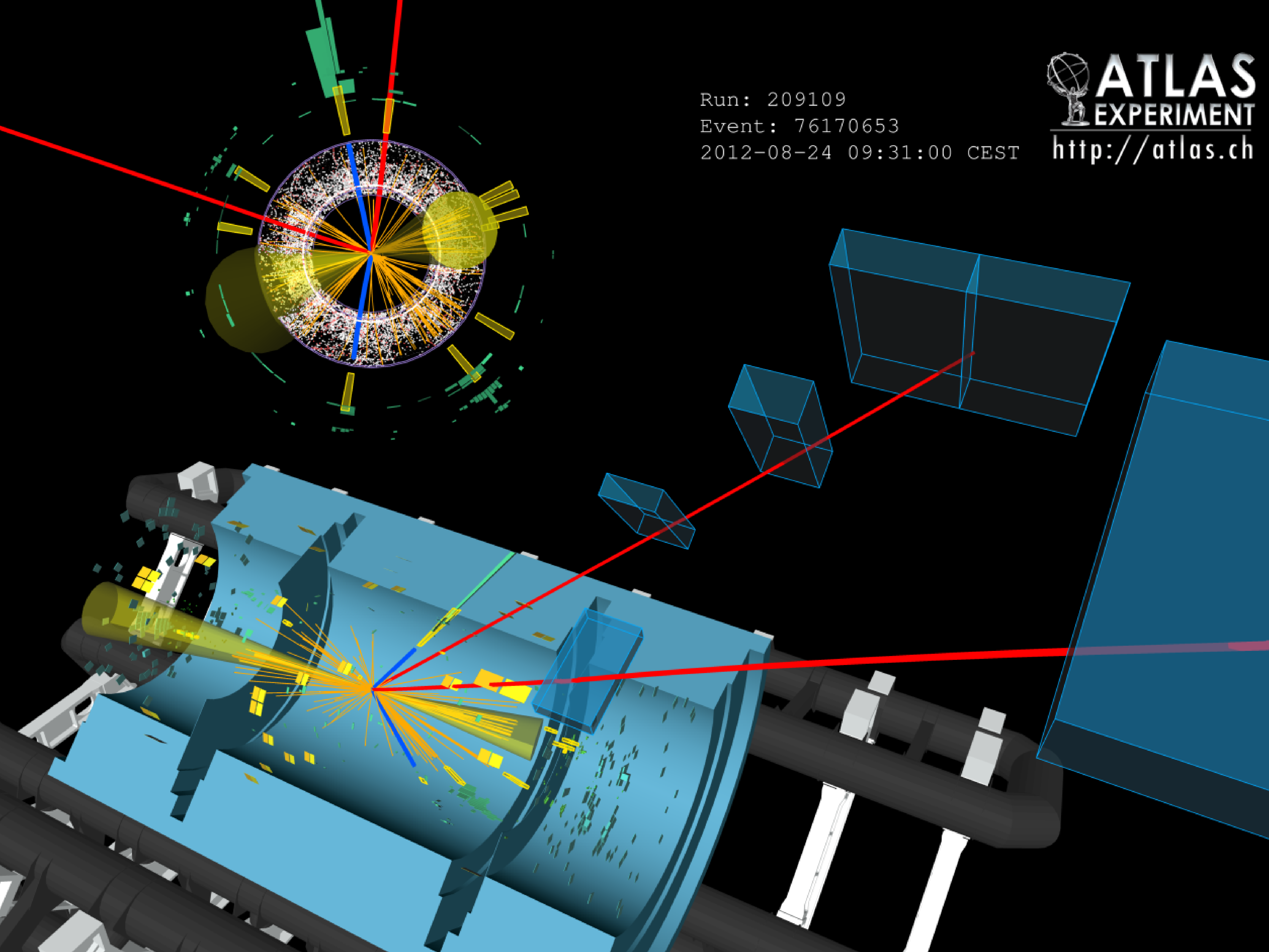
The 3200 terabytes of data that will be seen by ATLAS each year are the equivalent of the content in:

- 160 million trees made into books.
- 7 km (4 miles) of CD-ROMs stacked on top of each other.
- 600 years of listening to songs.
- 160 US Library of Congress (3 billion books).

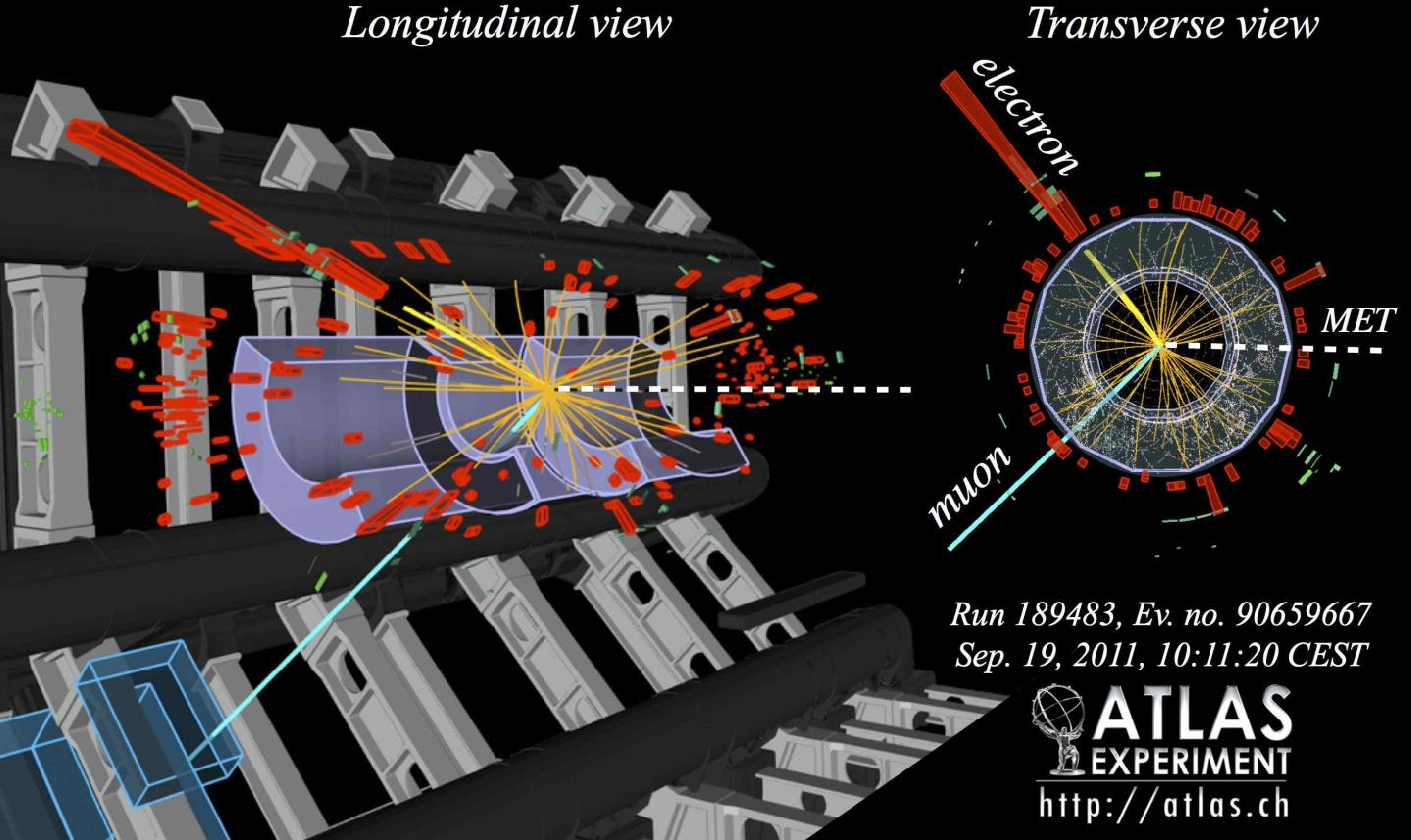
Weight ~ 7000 tonnes



Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch


Run: 209109
Event: 76170653
2012-08-24 09:31:00 CEST
ATLAS
EXPERIMENT
http://atlas.ch

(a) $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and no jets



The LHC and the ATLAS perform very well

- *Many precise measurements*
- *2012: Discovery of Higgs boson*
- *The Standard Model has become the Standard Theory*
- *No new physics found till now*
- *Is this the end?*

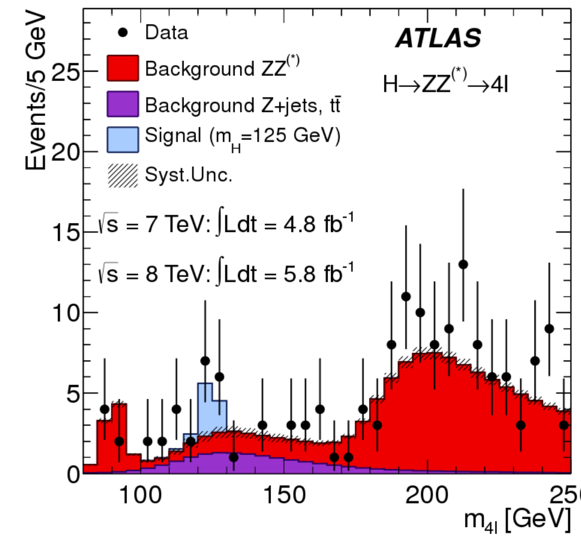
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

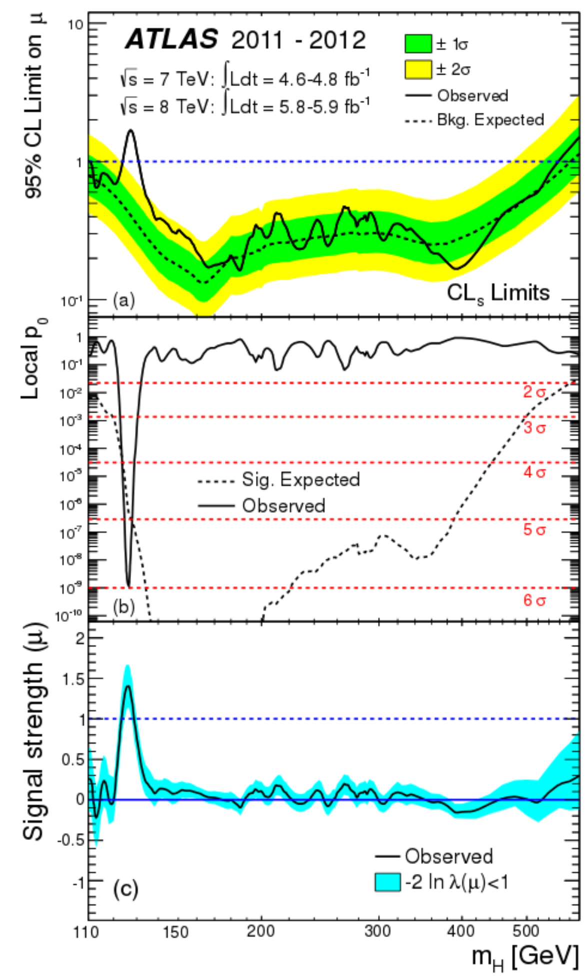
The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\mathrm{stat}) \pm 0.4\,(\mathrm{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.





It is (most likely) not the end

- ➔ There seems to be something beyond the standard theory
- Many unanswered fundamental questions all based on experimental observations, e.g.
  - What is the composition of dark matter?
  - Why is gravity so weak?
  - What is the origin of the matter-antimatter asymmetry in the universe?
  - What is the origin of the universe's accelerated expansion?

  . . .
- ➔ New Physics?
  - Many diverse theoretical ideas, e.g.
    - New heavy particle, Z' boson
    - Extra space dimensions

    . . .
- ➔ Search for new physics:
  - Direct searches for new heavy particles

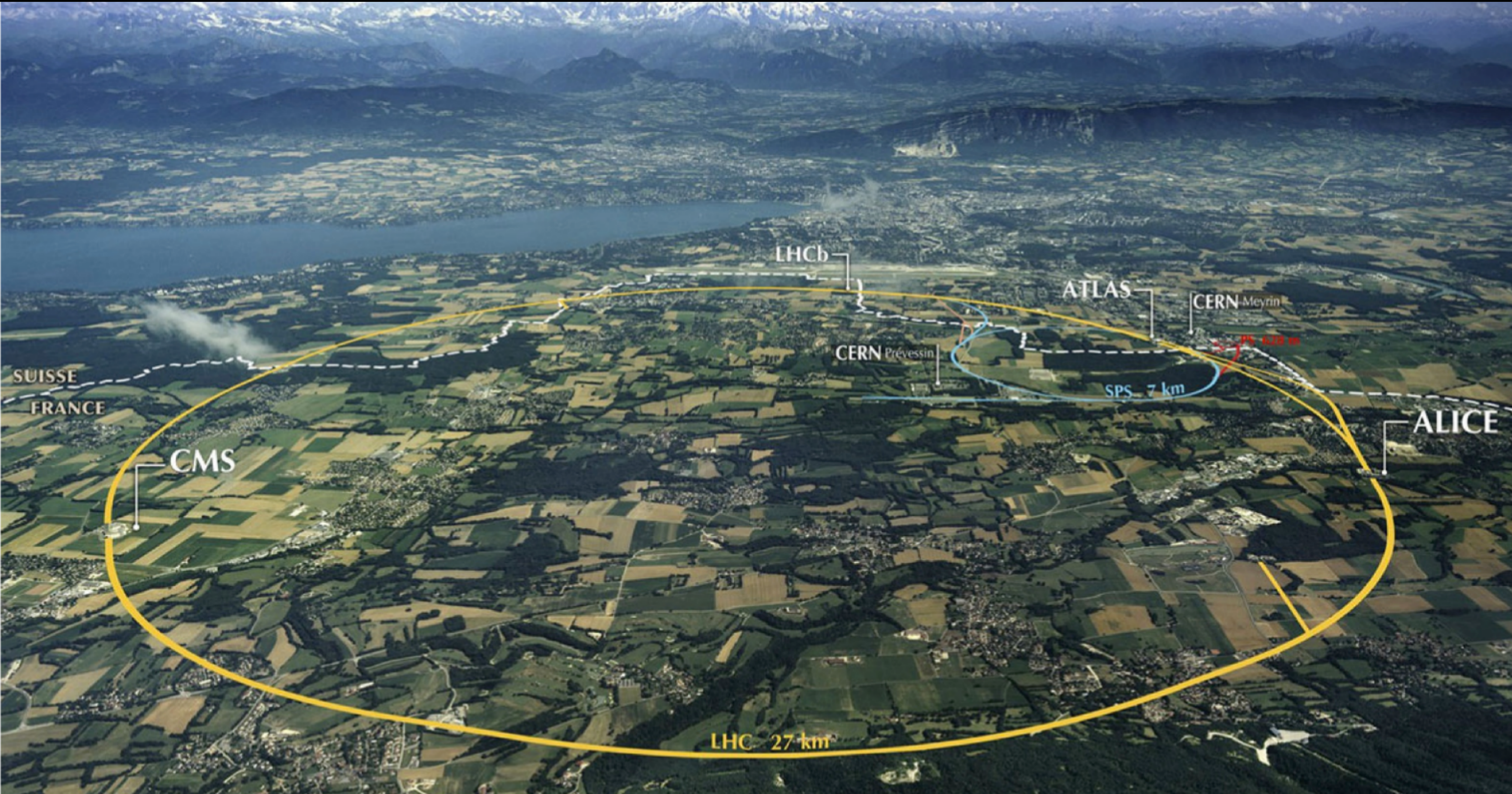
    Need colliders with ***larger energies***
  - Search for the imprint of new physics on the *W*, *Z*, *top*-quark, and *Higgs* properties

    New colliders / measurements with ***unprecedented accuracy***

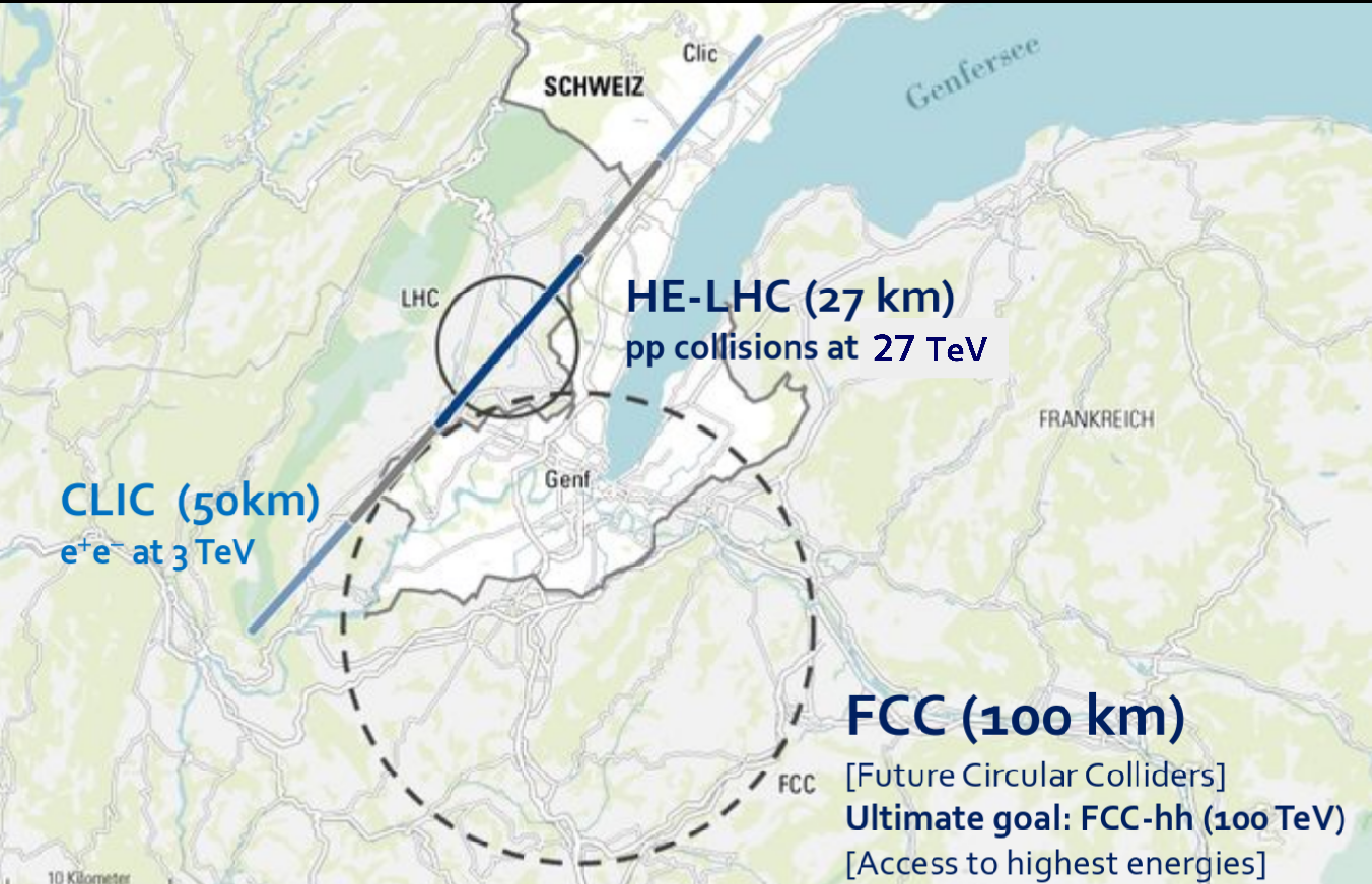
Short-term perspectives (2020-2035)

Exploit the full potential of the LHC

- ✔ Get 75-100 fb^{-1} at 13-14 TeV by 2018 (LHC Run2: running)
- ✔ Get ~300 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
- ✔ Upgrade machine and detectors to get 3000 fb^{-1} at 14 TeV by 2035 (HL-LHC: approved)



Long-term perspectives (2045-2080)



HE-LHC (27 km)
pp collisions at 27 TeV

CLIC (50km)
e^+e^- at 3 TeV

FCC (100 km)
[Future Circular Colliders]
Ultimate goal: FCC-hh (100 TeV)
[Access to highest energies]

Conclusions

- Particle Physics describes the smallest structures in the universe
- Theory: The Standard Model works fabulously well
- Many big mysteries to solve
- The ATLAS continues to explore the 14 TeV frontier