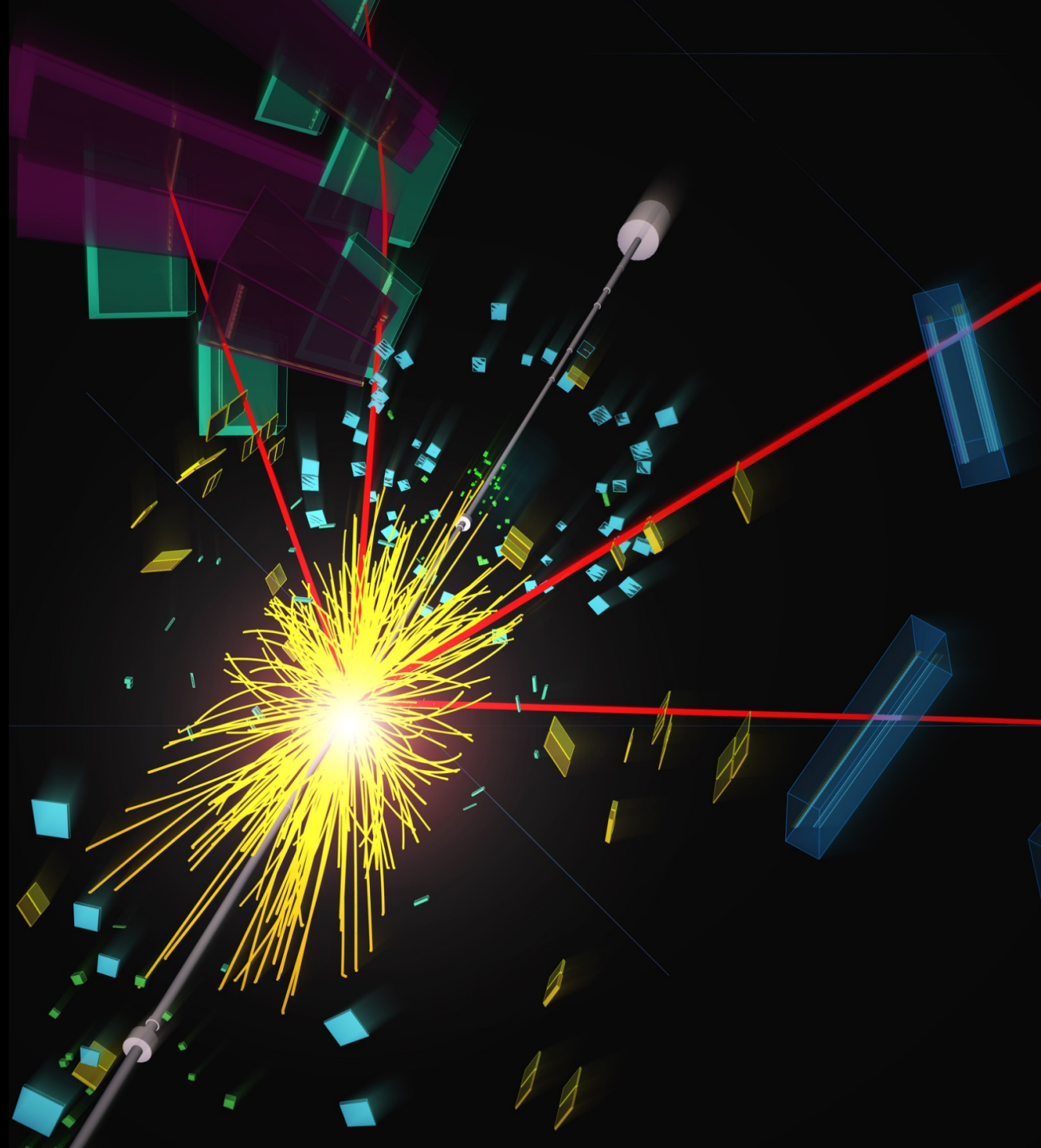


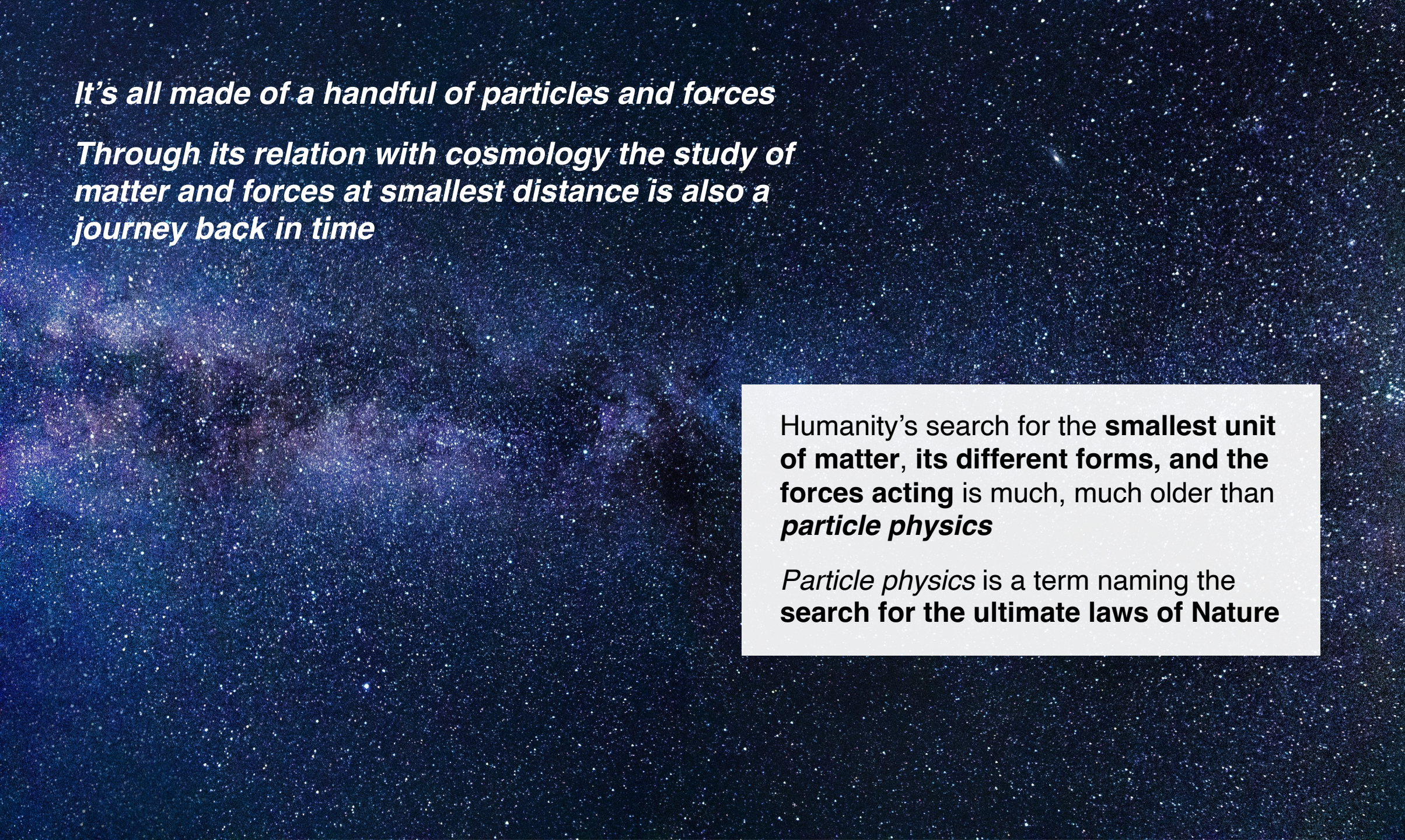
# Smashing discoveries — the Large Hadron Collider at CERN

From the Higgs boson to the quest for  
new physics

Andreas Hoecker (CERN)  
Colloquium, Pisa, 29 June 2022







*It's all made of a handful of particles and forces*

*Through its relation with cosmology the study of matter and forces at smallest distance is also a journey back in time*

Humanity's search for the **smallest unit of matter, its different forms, and the forces acting** is much, much older than *particle physics*

*Particle physics* is a term naming the **search for the ultimate laws of Nature**



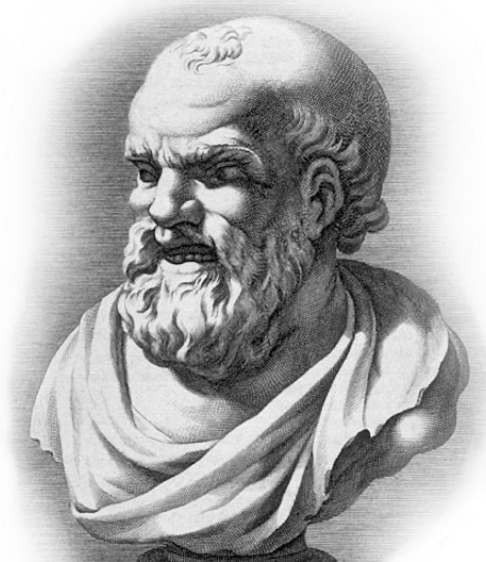
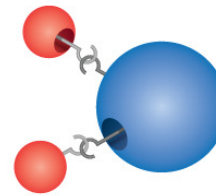
# Setting the stage

About 2500 years ago, the Greek “laughing philosopher” Democritus developed a new doctrine: **atomism** (atomos = indivisible)

*Two realities would compose the natural world: **atoms** and **void***

Atoms are infinite in number and various in size and shape, and perfectly solid, with no internal gaps. Atoms may combine into clusters by means of tiny hooks and barbs on their surfaces, which become entangled.

Atoms move in an infinite void.



Democritus (460–370 BC)

Since these times, philosophers, mathematicians, astronomers, physicists, chemists have tried to understand the laws of matter and the forces acting on them, to find answers to the fundamental question of “How”, and hoping to also get some insight into the “Why”

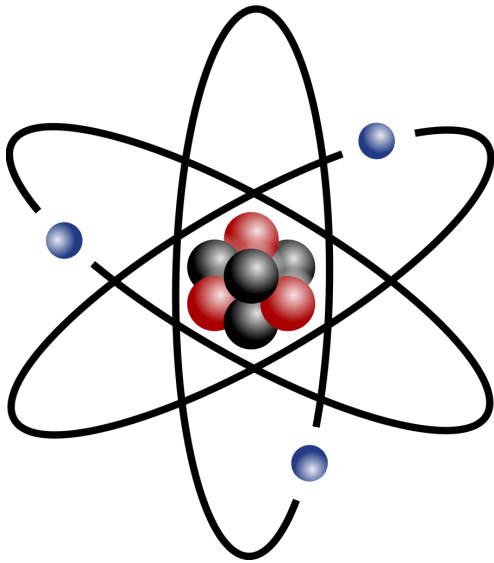
**Democritus relied on phenomenology, since the scientific revolution physicists rely on observation and mathematics to study and describe the physical laws**



# Setting the stage

---

Today, you all know what atoms are, and we know they exist as we can count them one by one



Light electrons surround a nucleus made of heavy protons and neutrons like planets the sun...

Really? This classical picture fails in many respects. Only quantum mechanics, developed in the 1920s was able to provide a mathematical description of the atom. Heisenberg understood that the “trajectories” are imagined, and only exist when we observe them (one among a distribution of options occurred)

We still do not know what an atom really is, but we can compute all its properties along statistical probabilities following strict physical law



Werner Heisenberg  
(1901–1976)

**Physical laws are thus not what is *in the* Nature, but our way to *describe* Nature**

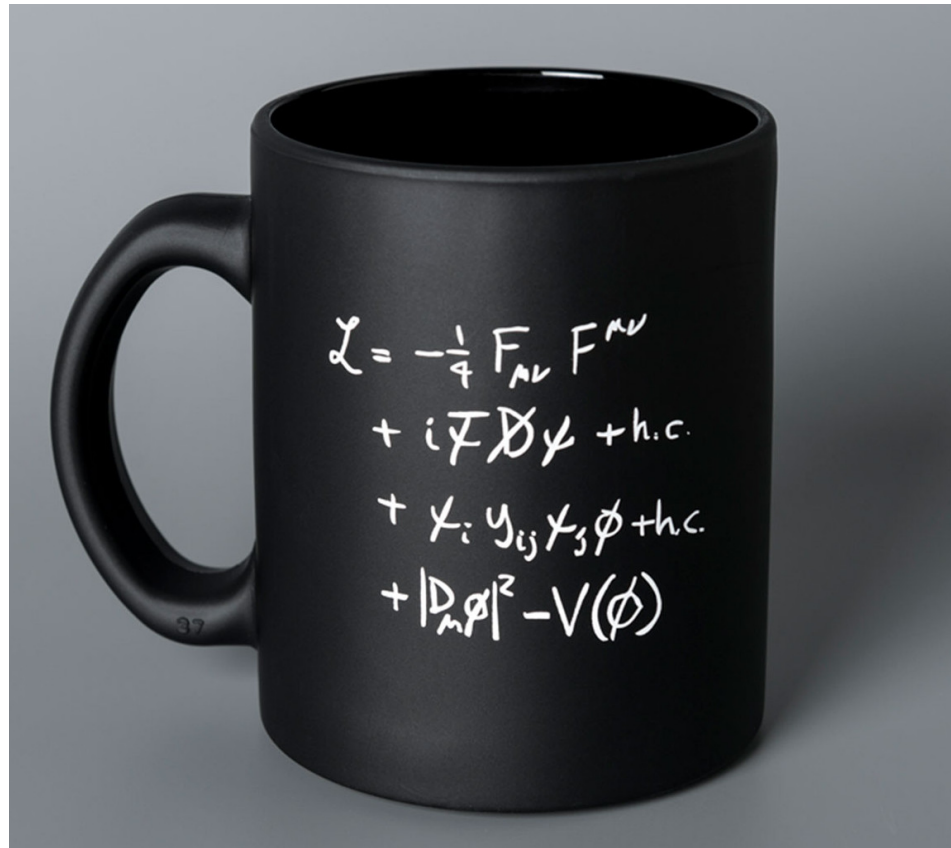


# Everyday life and particle physics are described by the Standard Model

Since the birth of quantum mechanics, physicists of the twentieth century have developed the **Standard Model**, a *quantum field theory* which describes all known forms of matter and forces, except gravity

The Standard Model unifies quantum mechanics, special relativity and field theory

It also unifies electromagnetic and weak interactions



It can be written in a very compact form so that it fits on a mug



# The Standard Model

Since the birth of quantum mechanics, physicists of the twentieth century have developed the **Standard Model**, a *quantum field theory* which describes all known forms of matter and forces, except gravity

The **Lagrangian** allows to derive the equations of motion of a system

This term is related to the **Higgs sector**

It was postulated before the LHC but not experimentally confirmed

These terms describe **interactions among force particles (top) and among matter and force particles (bottom)**

This part was experimentally probed to good precision before the start of the LHC

The top term describes how **matter particles couple to the Higgs field  $\phi$  and thereby obtain mass**

The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

The lower right term describes the **Higgs potential  $V(\phi)$  with a non-zero ground state**

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\chi}_i Y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



# The Standard Model

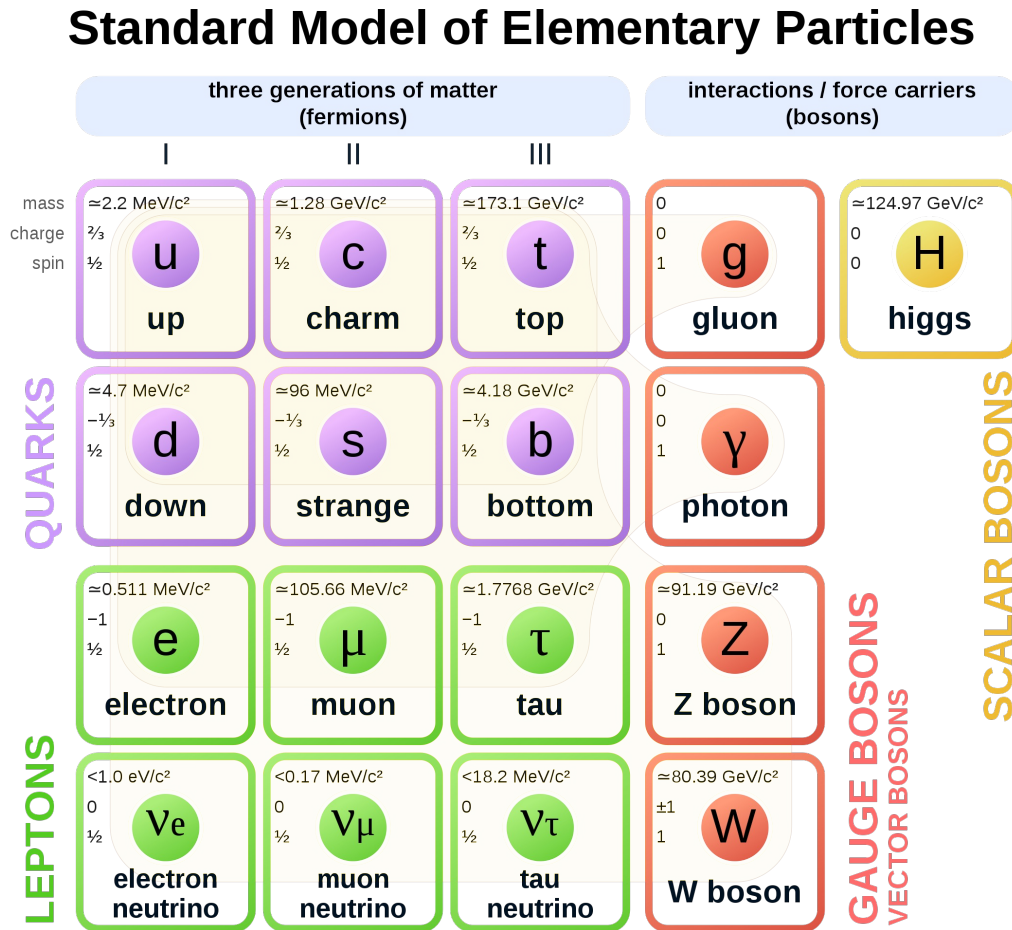
In its full (and rather frightening) form, the Standard Model looks like this

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)) - \\
 & ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
 & g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & gMW_\mu^+ W_\mu^- H - \frac{1}{2}g\frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g\frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - ig\frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig\frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig s \lambda_{ij}^a (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a - \dots
 \end{aligned}$$

$$\begin{aligned}
 & \dots - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\nu^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$

# The Standard Model

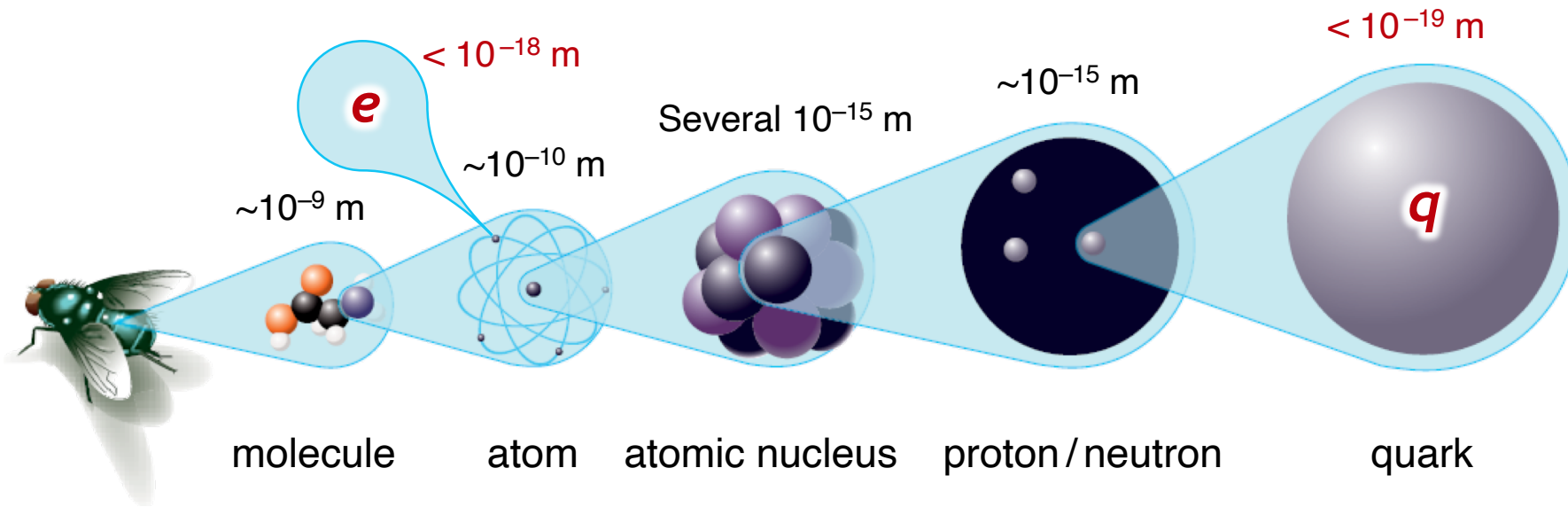
These equations describe all known particles and their interactions





# The Standard Model

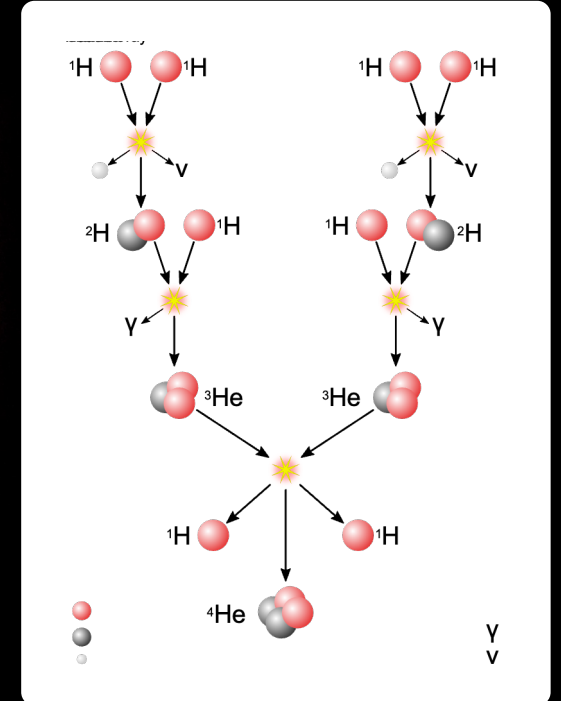
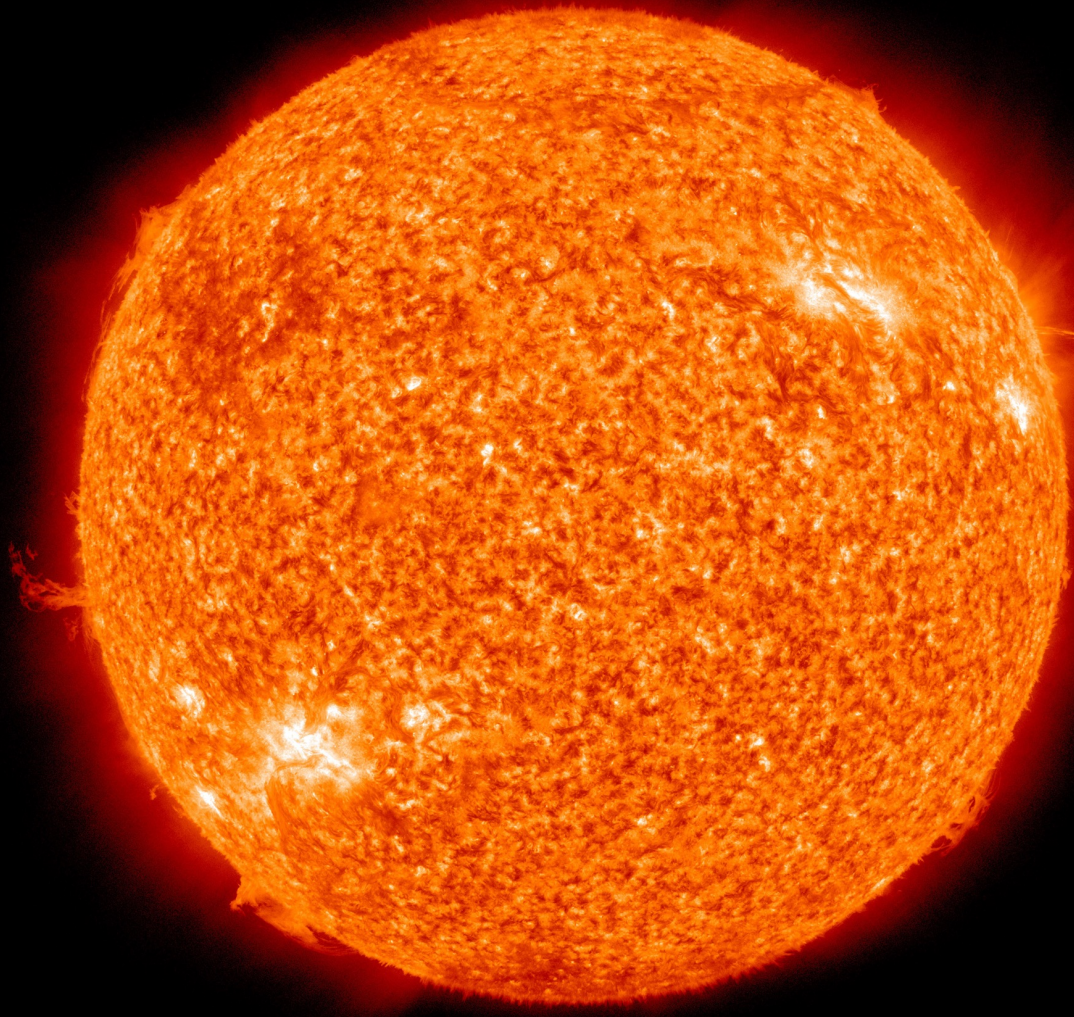
The Standard Model describes the properties of macroscopic objects, molecules, atoms, the atomic nucleus, the structure of the protons and neutrons



In the Standard Model, the elementary particles have no substructure, they are “point-like”. All experimental attempts to resolve further substructure have failed so far. Most physicists believe there must be some form of tiny structure ...

# The Standard Model

The Standard Model does not only describe the tiniest objects in space, it also explains how, e.g. the Sun burns

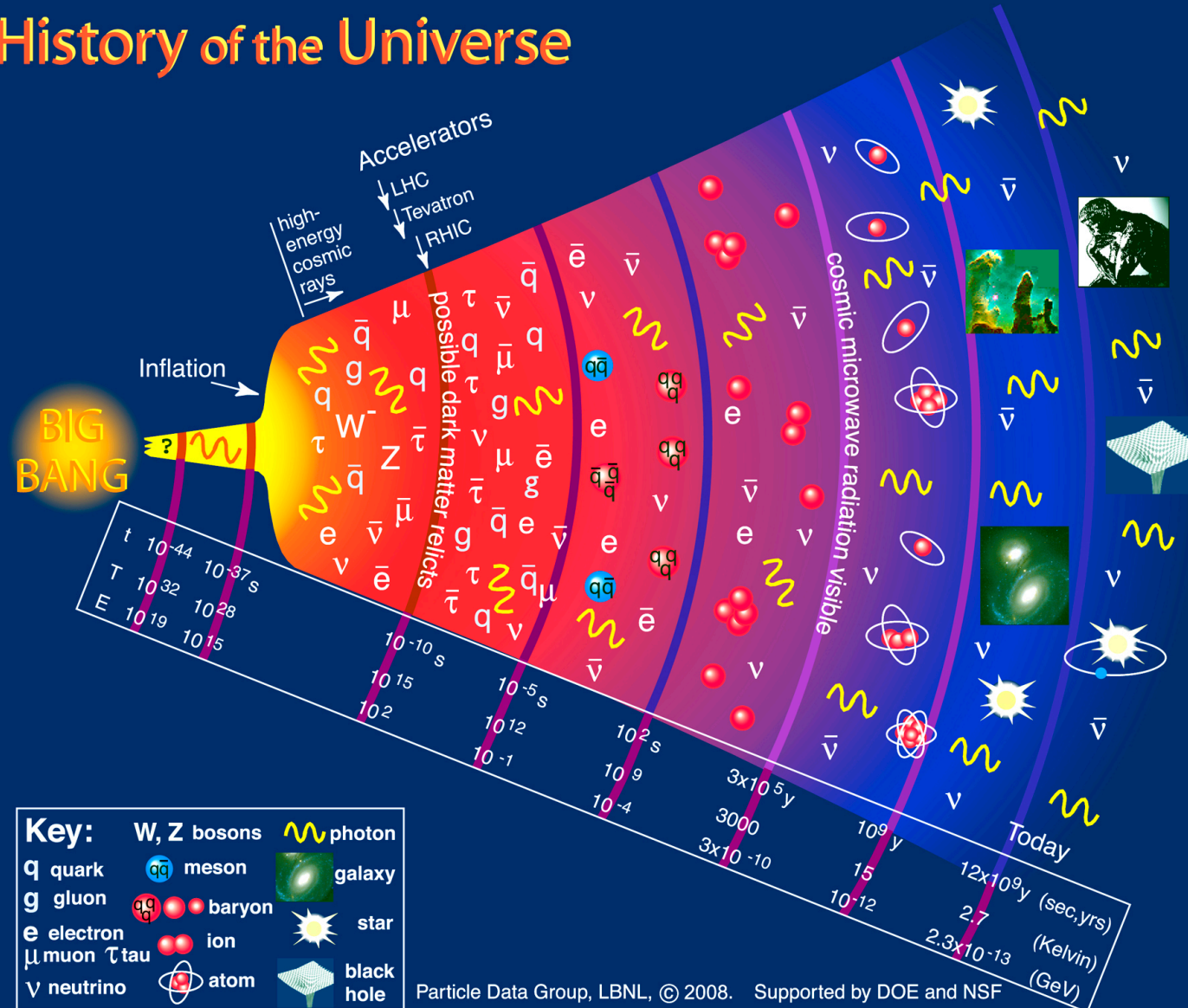




# The Standard Model

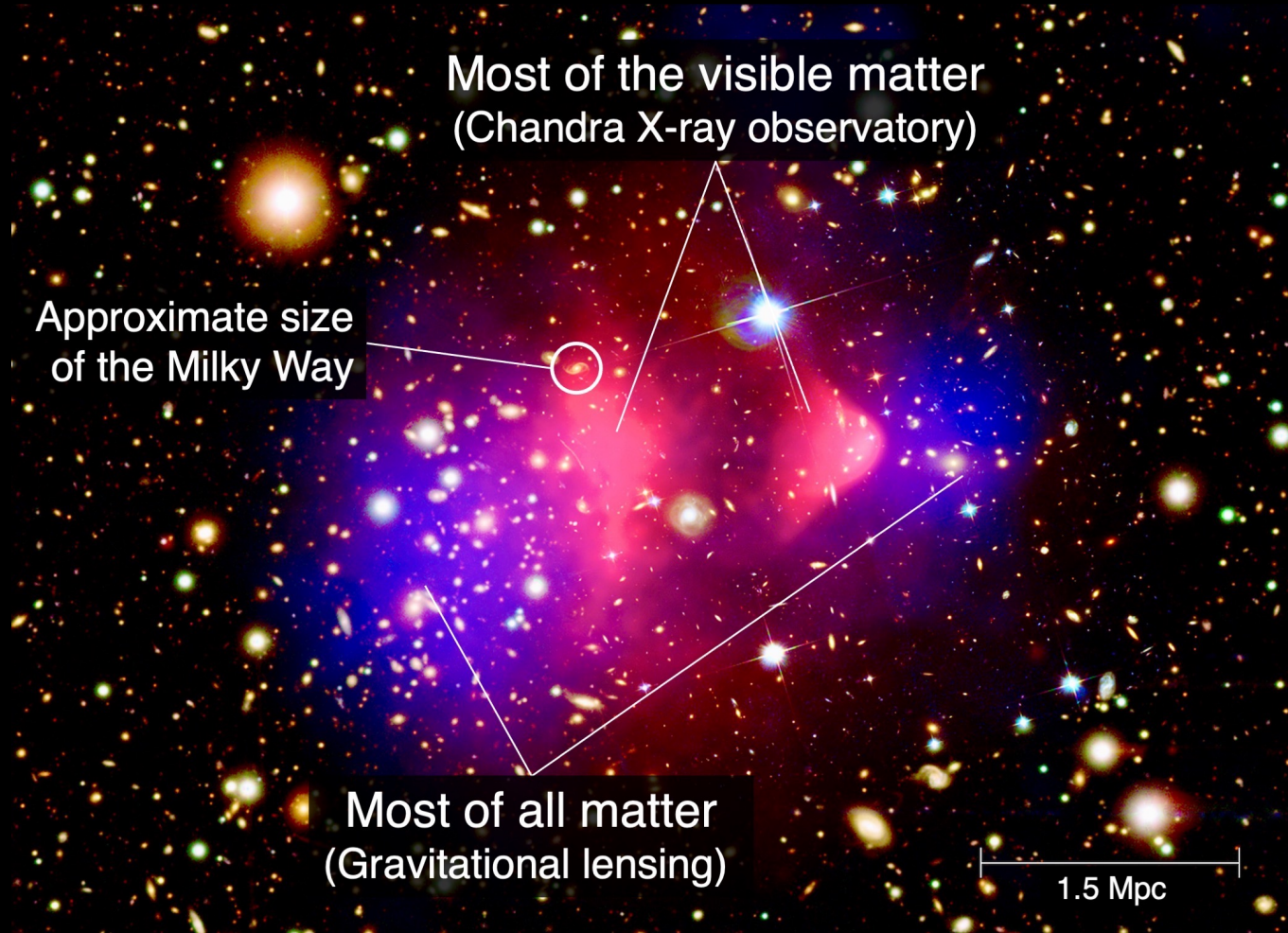
... and should describe the full history since the Big Bang, 13.8 billion years ago

## History of the Universe

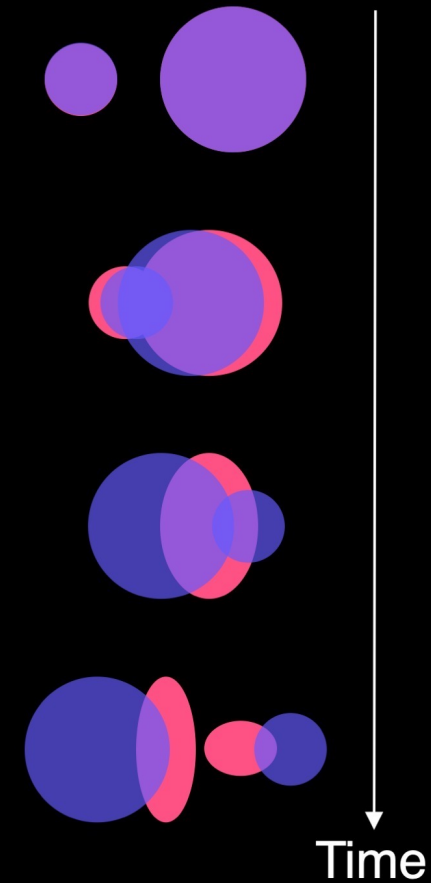


# The Standard Model

... but something is wrong



Bullet Cluster: one among many evidences of gravitational dark matter





# The Higgs mechanism

A very simplifying picture!

**Fundamental “gauge” symmetry** requires all force and matter particles to be massless

Early universe: symmetric phase,  
fundamental particles are massless  
→ gauge symmetry is respected

## *Symmetric phase – early universe*

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

# The Higgs mechanism

A very simplifying picture!

Masses can be dynamically generated by **spontaneously breaking electroweak symmetry**

The universe expands and cools down, after about  $10^{-11}$  seconds after the big bang electroweak symmetry breaks

A Higgs field displaces ground state breaking gauge symmetry

It fills all space time (but without orientation as it has no spin)

Particles interact with Higgs field and effectively reduce their velocity. Acquired mass proportional to interaction strength

→ Action of the Higgs field creates “vacuum viscosity” (caution — not quite!)

## *Higgs quantum liquid in broken phase*

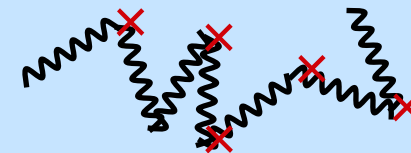
Gravity



Photon



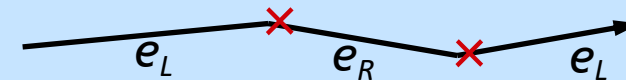
Weak boson



Neutrinos



Electrons



Top quark



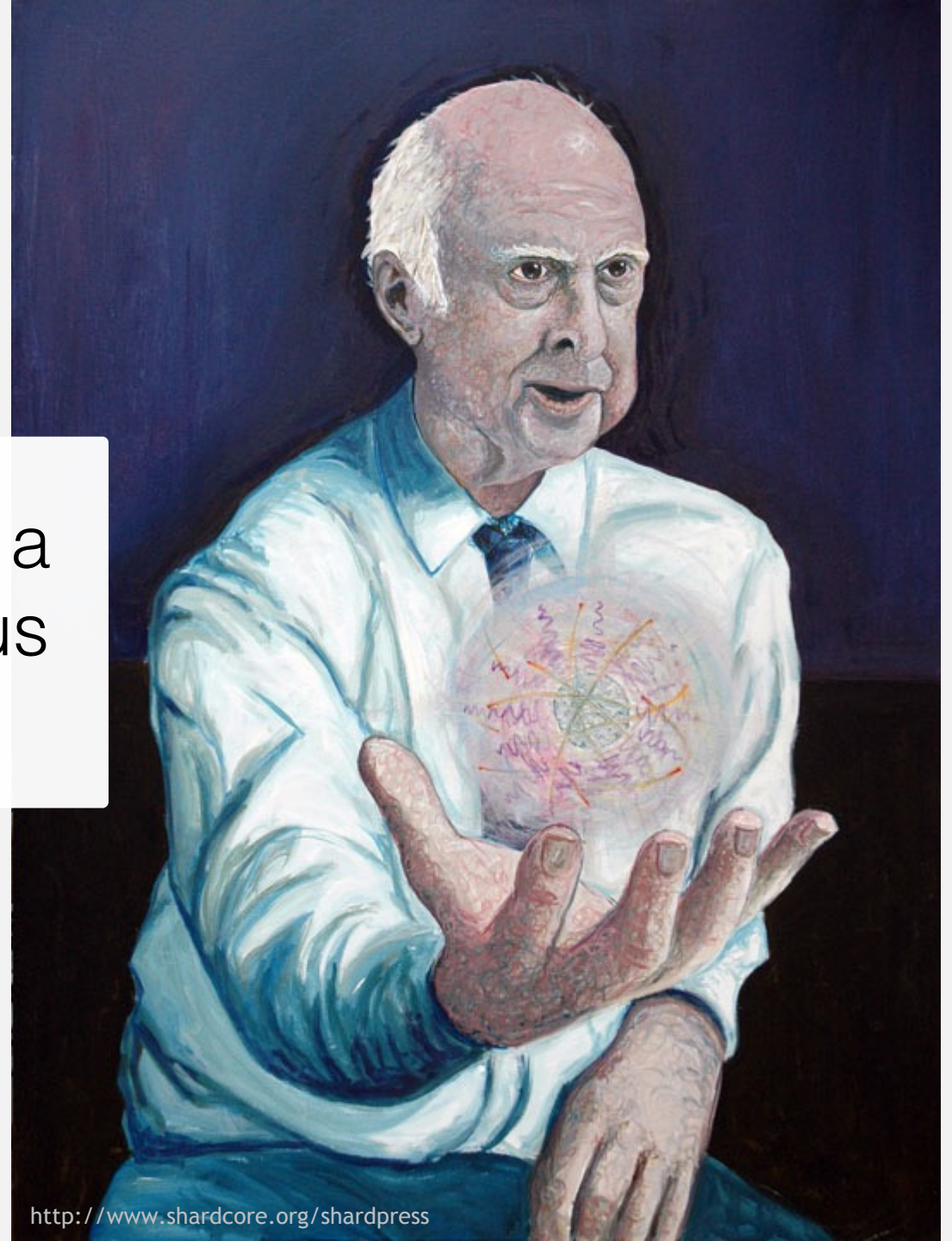
Interaction with Higgs field alters chirality of massive Dirac fermion



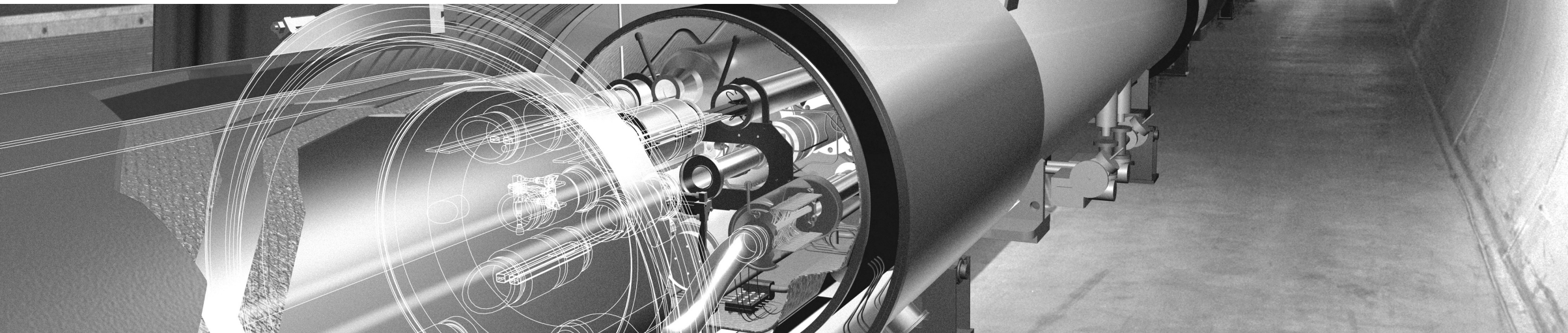
The Higgs mechanism was only a hypothesis before the LHC

To prove it one had to find a new particle: the mysterious  
**Higgs boson**

If the Higgs boson existed, it had to be rather massive and its production would be rare



# Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine



**Lawrence**  
(First cyclotron  
provided 80 keV  
proton acceleration)

## Particle accelerators

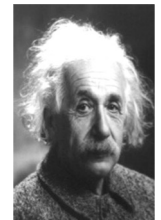
- Look deeper into matter (size  $\sim 1/E$ ) (powerful microscope)
- Discover new heavier particles ( $E = mc^2$ )
- Probe conditions of the early universe ( $E = kT$ )



de Broglie



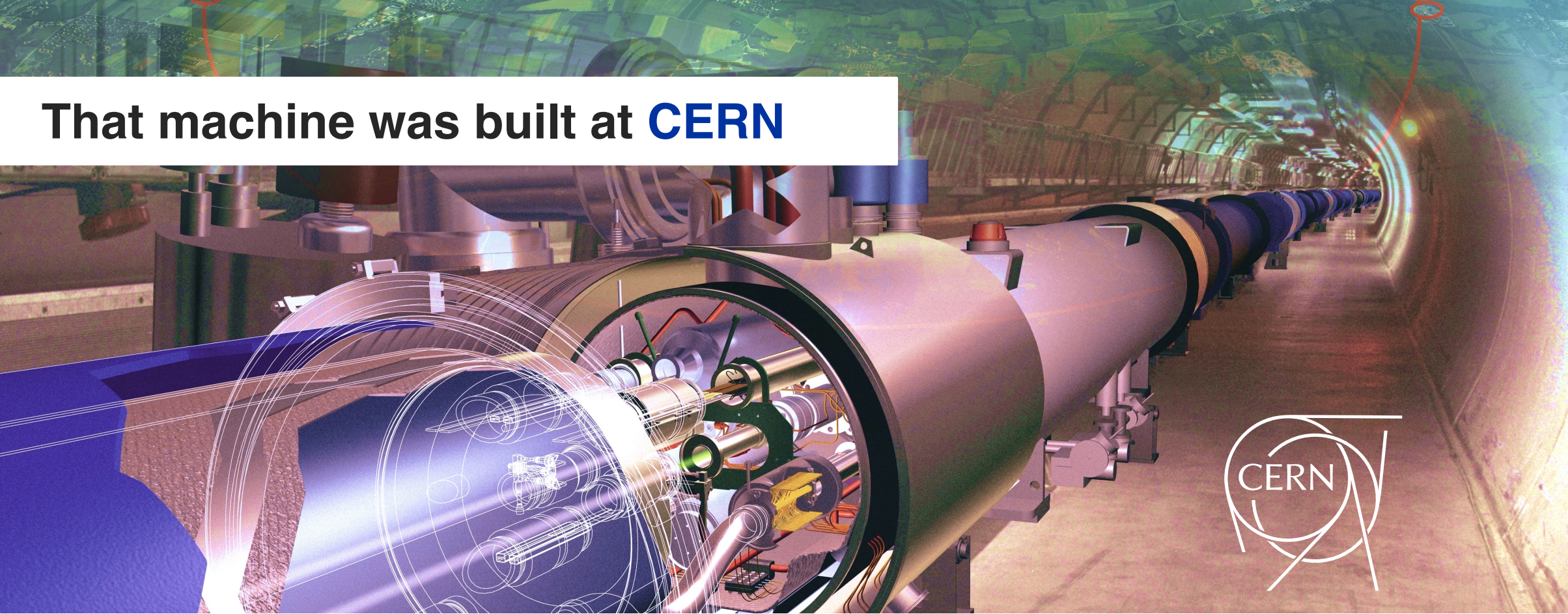
Boltzmann



Einstein



That machine was built at **CERN**



**CERN**

Founded in 1954 has become a  
paradigm for Scientific Cooperation





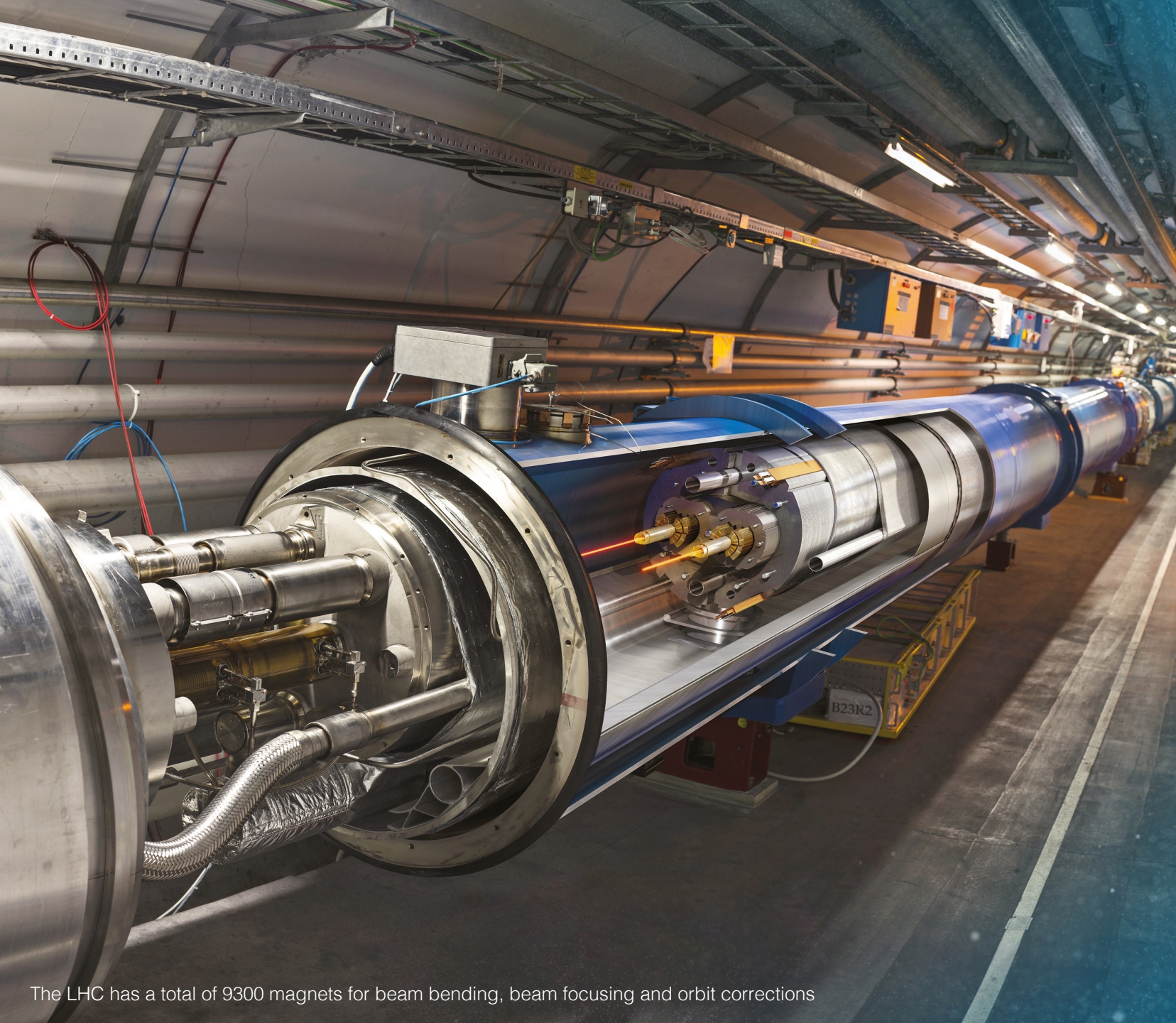
# CERN today

CERN is the world's biggest laboratory for particle physics located near Geneva, Switzerland

Its mission is to understand the most fundamental particles and laws of the universe







# Large Hadron Collider (LHC)

- 27 km in circumference
- About 100 m underground
- Superconducting magnets steer the particles around the ring
- Proton and ions are accelerated to close to the speed of light

The LHC has a total of 9300 magnets for beam bending, beam focusing and orbit corrections





CMS

LHC

LHC

CERN  
Preessin

ALICE >>

ATLAS

<< LHCb

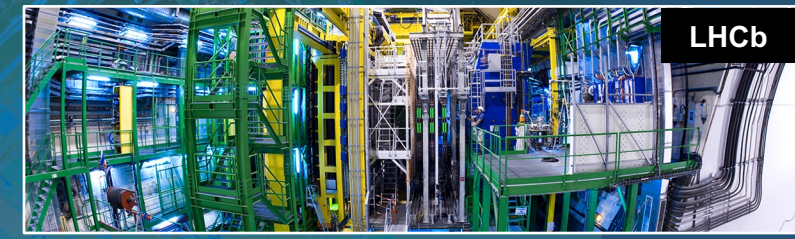
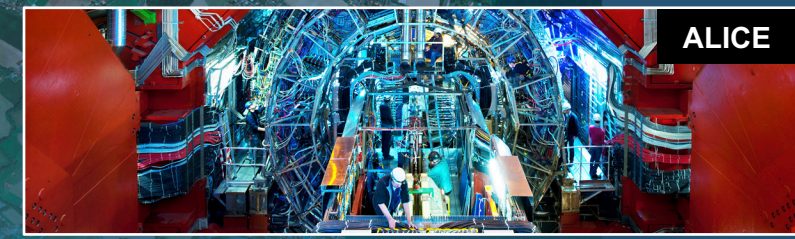
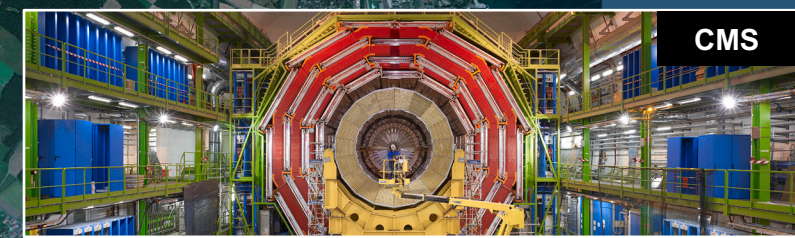
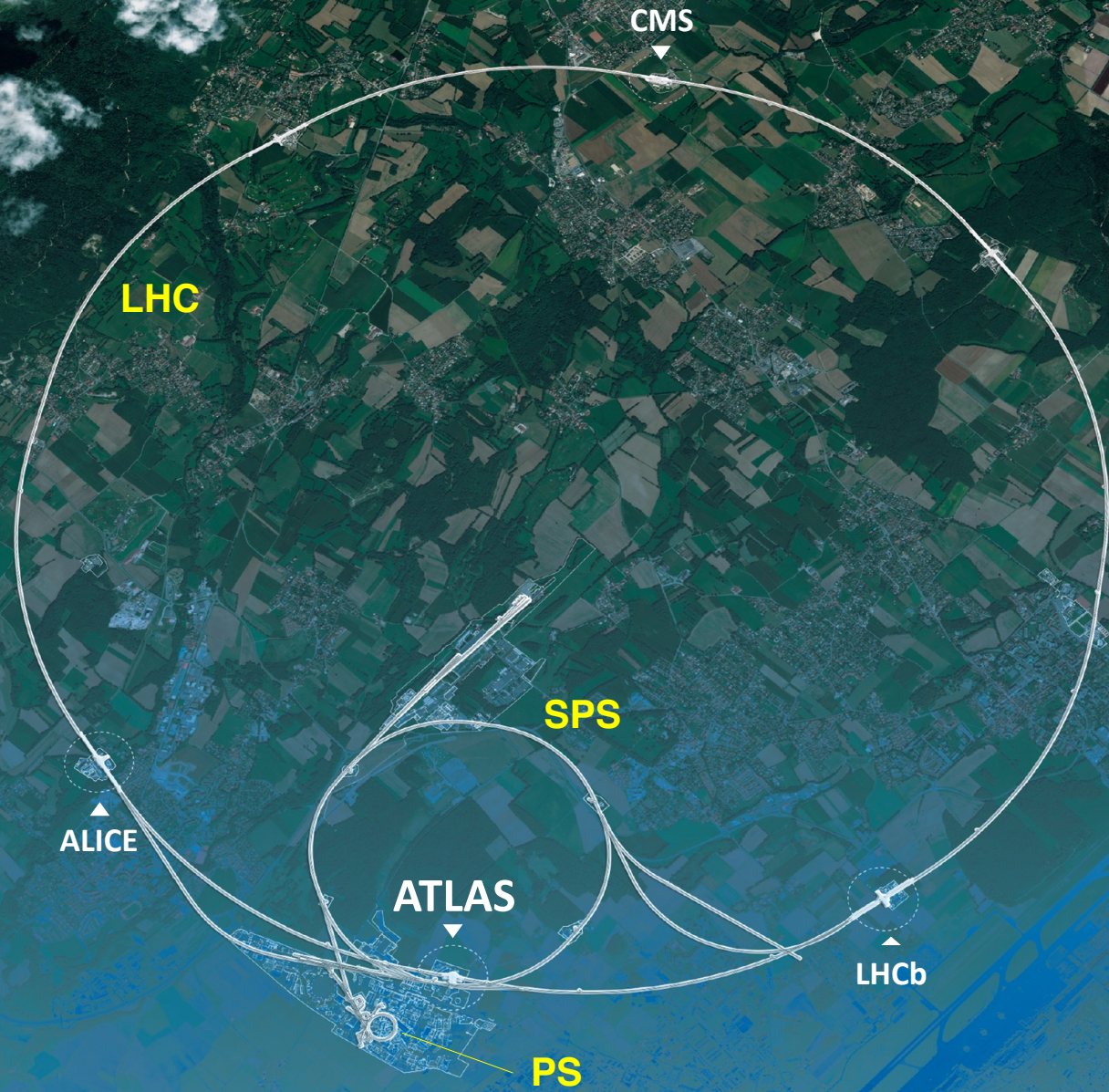
CERN  
Meyrin

LHC — areal view

1 km



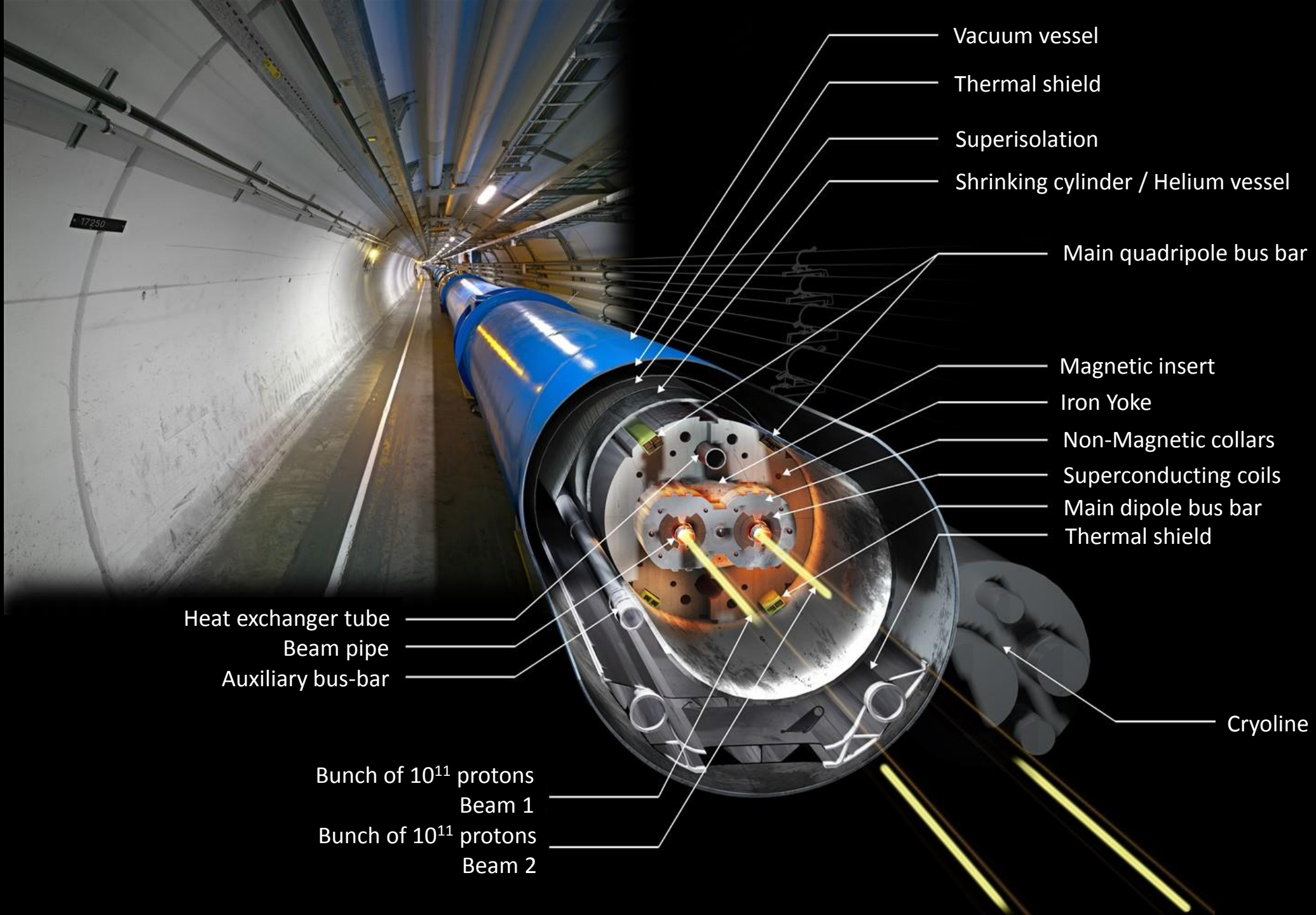
# LHC — areal view











Vacuum vessel

Thermal shield

Superisolation

Shrinking cylinder / Helium vessel

Main quadripole bus bar

Magnetic insert

Iron Yoke

Non-Magnetic collars

Superconducting coils

Main dipole bus bar

Thermal shield

Cryoline

Heat exchanger tube

Beam pipe

Auxiliary bus-bar

Bunch of  $10^{11}$  protons

Beam 1

Bunch of  $10^{11}$  protons

Beam 2





Vacuum vessel

Thermal shield

Superisolation

Shrinking cylinder / Helium vessel



LHC dipoles waiting for their installation in the tunnel



Lowering of the first dipole magnet into the tunnel on March 7<sup>th</sup> 2005

Cryoline

Bunch of  $10^{11}$  protons

Beam 1

Bunch of  $10^{11}$  protons

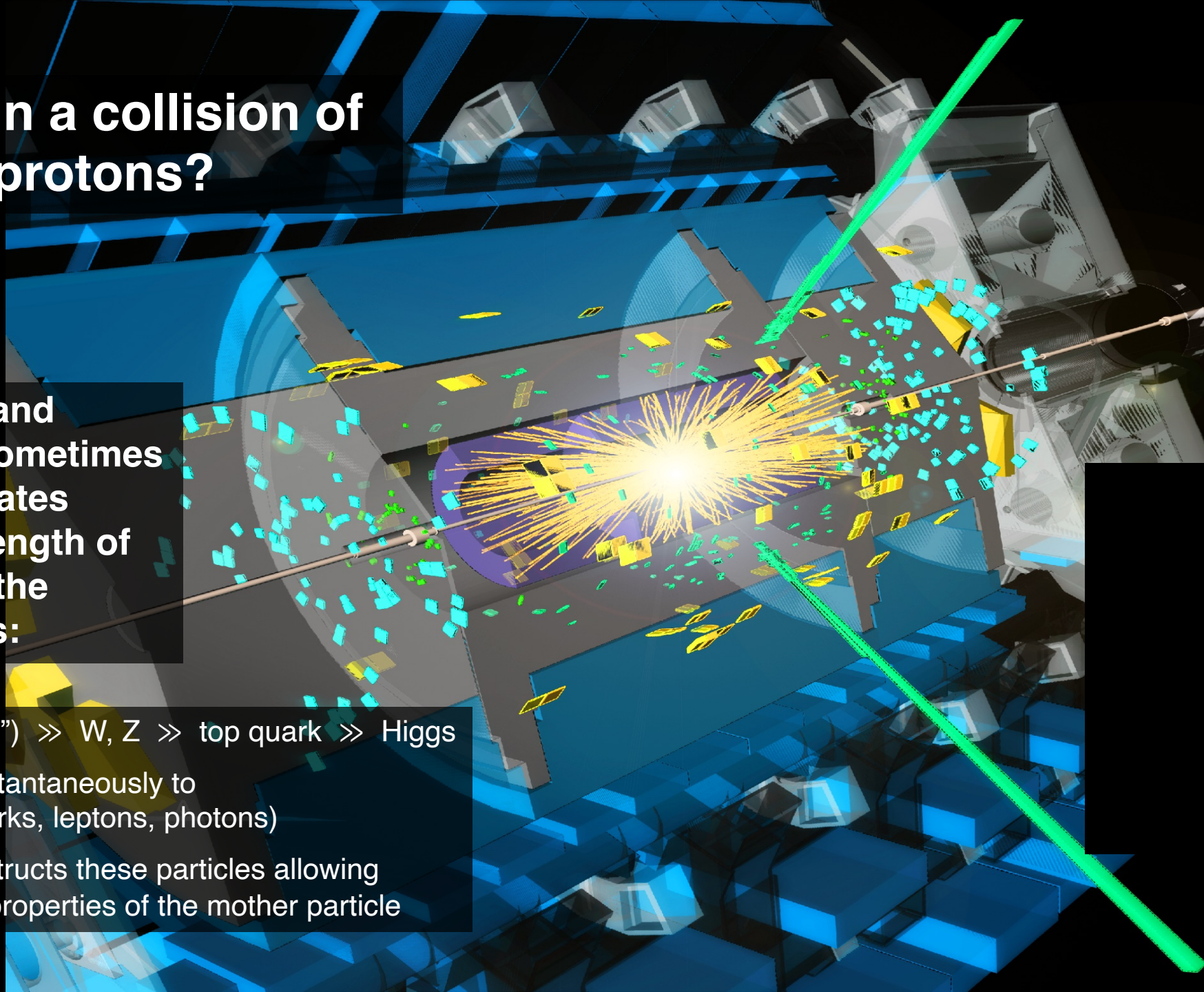
Beam 2



# What happens in a collision of high-energetic protons?

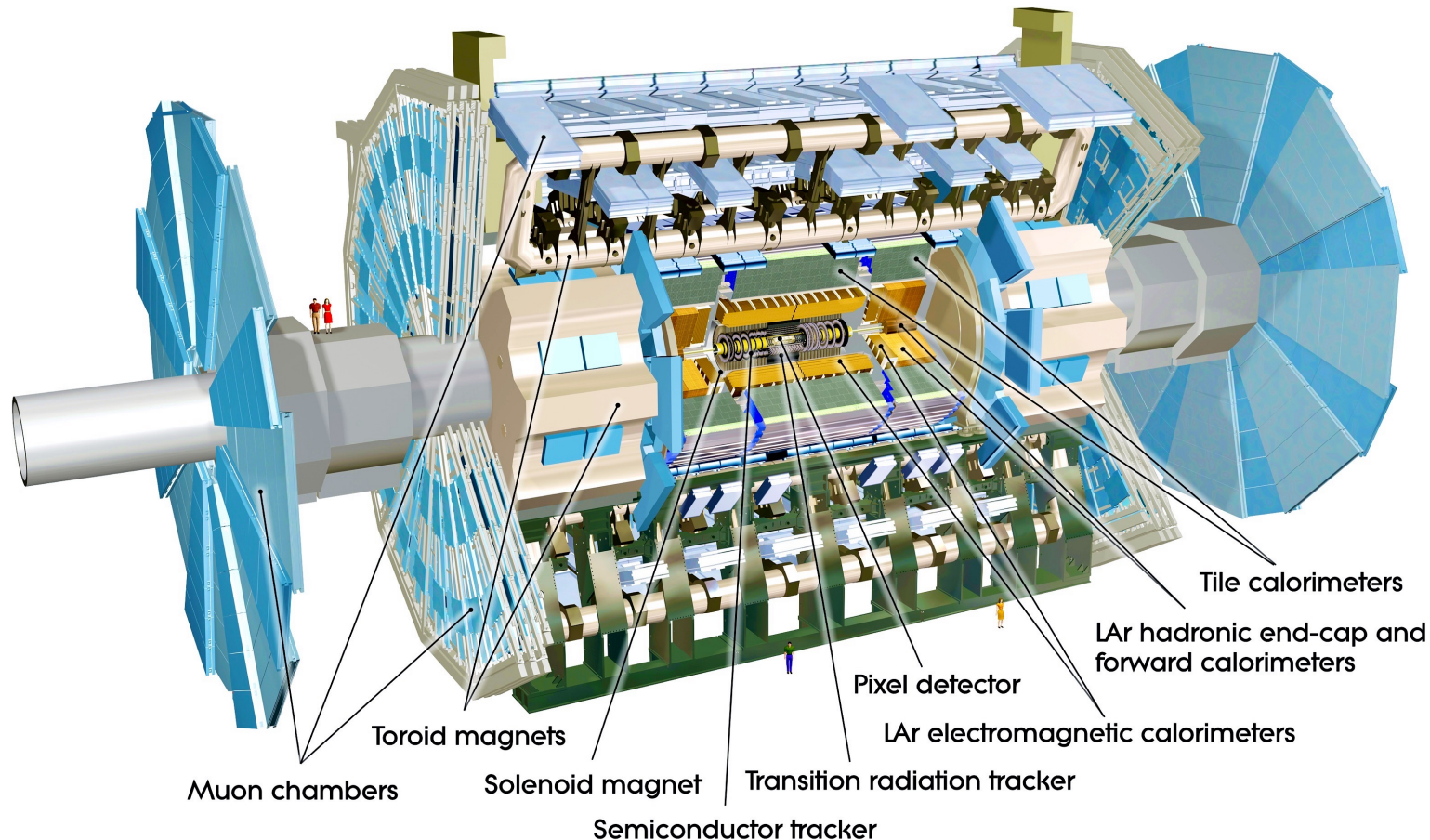
Its constituents fuse and transform into new, sometimes heavy particles with rates depending on the strength of their interaction with the proton and their mass:

- Light quarks, gluons (“jets”)  $\gg$  W, Z  $\gg$  top quark  $\gg$  Higgs
- Heavy particles decay instantaneously to light, stable particles (quarks, leptons, photons)
- A particle detector reconstructs these particles allowing physicists to deduce the properties of the mother particle

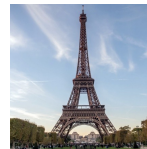




# The ATLAS Detector



25 m diameter, 46 m long, 7000 tons weight ~



Axial field provided by **solenoid** (2 T) in central region (momentum measurement)

High resolution silicon **detectors**:

- 100 Mio. channels ( $50\ \mu\text{m} \times 250\ \mu\text{m}$ )
- 6 Mio. channels ( $80\ \mu\text{m} \times 12\ \text{cm}$ )

spatial resolution  $\sim 15\ \mu\text{m}$  (in azimuthal direction)

Energy measurement down to  $1^\circ$  to the beam line with a **calorimeter system**

Independent **muon spectrometer** (superconducting toroid system)

Ultra-fast custom electronics filters the collisions: only 1 out of 30,000 collisions is kept!



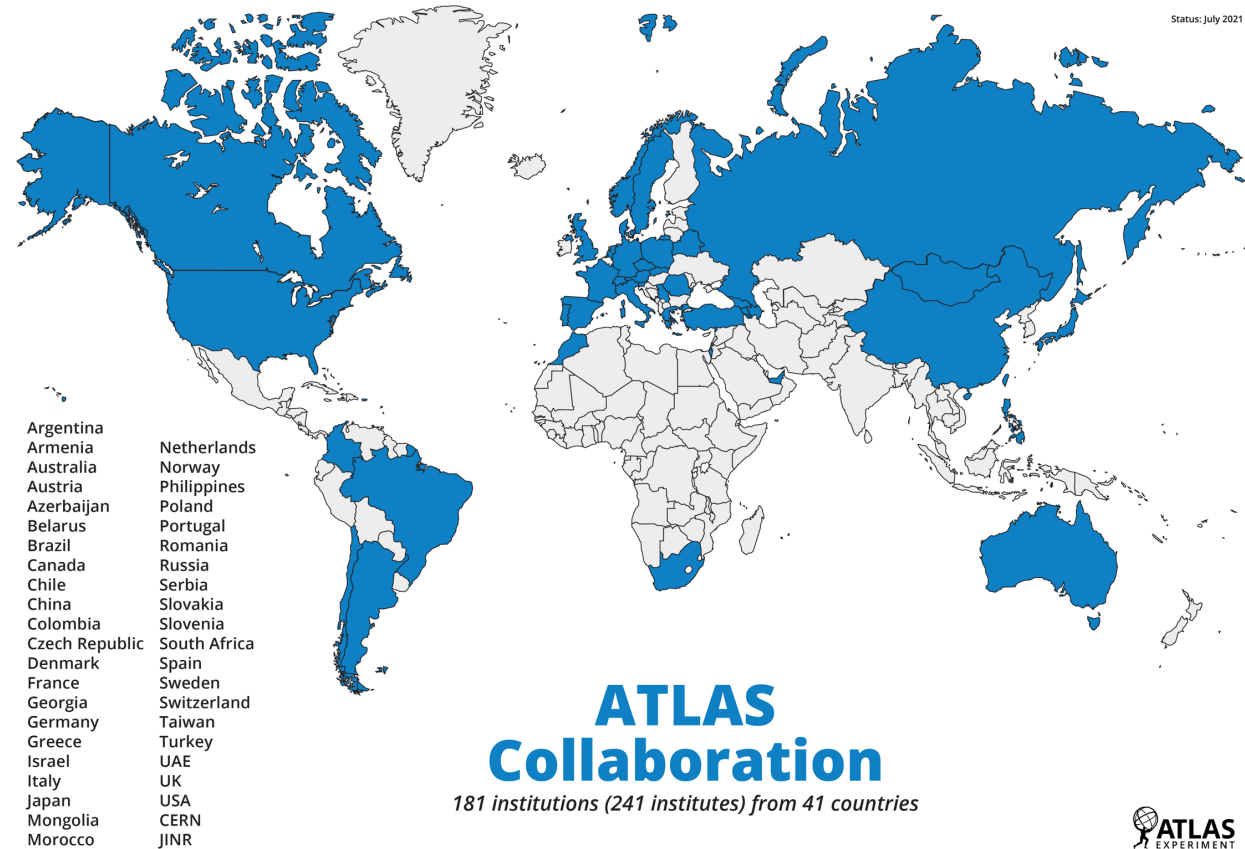
# ATLAS Collaboration

The LHC and its experiments are technological prowess **designed, built, operated and upgraded by large international consortia (→ collaborations)**

They offer scientific research at the energy frontier, technological breakthroughs, highest level education, international cooperation

## The ATLAS Collaboration

- 6000 physicists, engineers, technicians from 103 nationalities
- 2900 scientific authors
- 1200 PhD students
- 244 institutes from 42 countries
- 1072 scientific papers





# CERN offers various renowned educational programmes



## The ATLAS Collaboration

- 5900 physicists, engineers, technicians from 103 nationalities
- 2900 scientific authors
- **1200 PhD students**
- 243 institutes from 41 countries
- 1024 scientific papers





# ATLAS Detector construction and installation

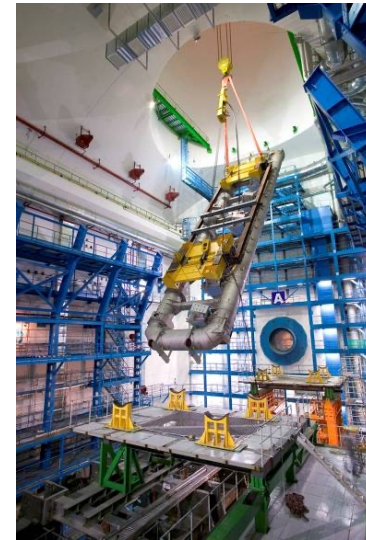


ATLAS cavern after excavation in July 2002

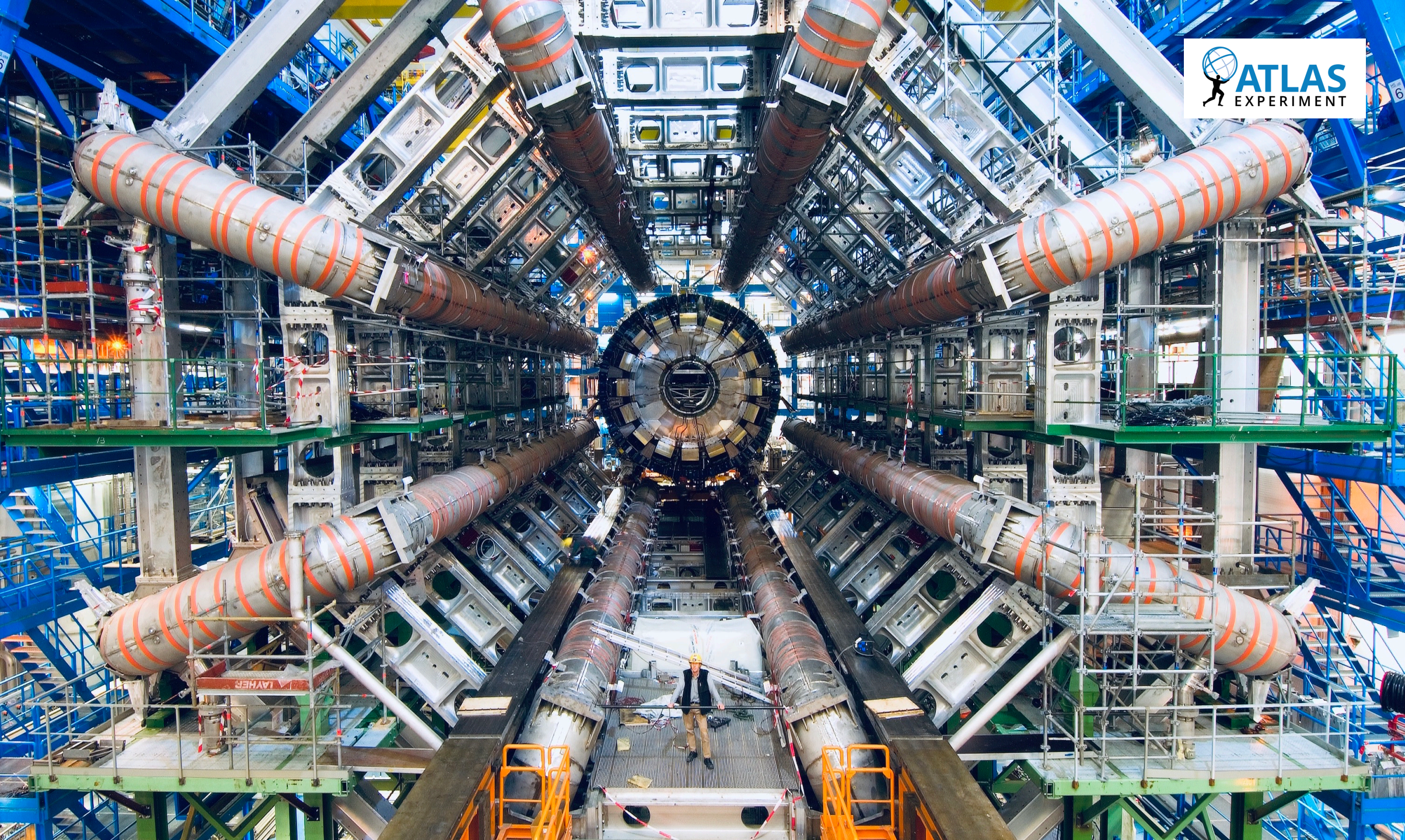
- 53 m long
- 35 m high (10-storey building)
- 30 m wide



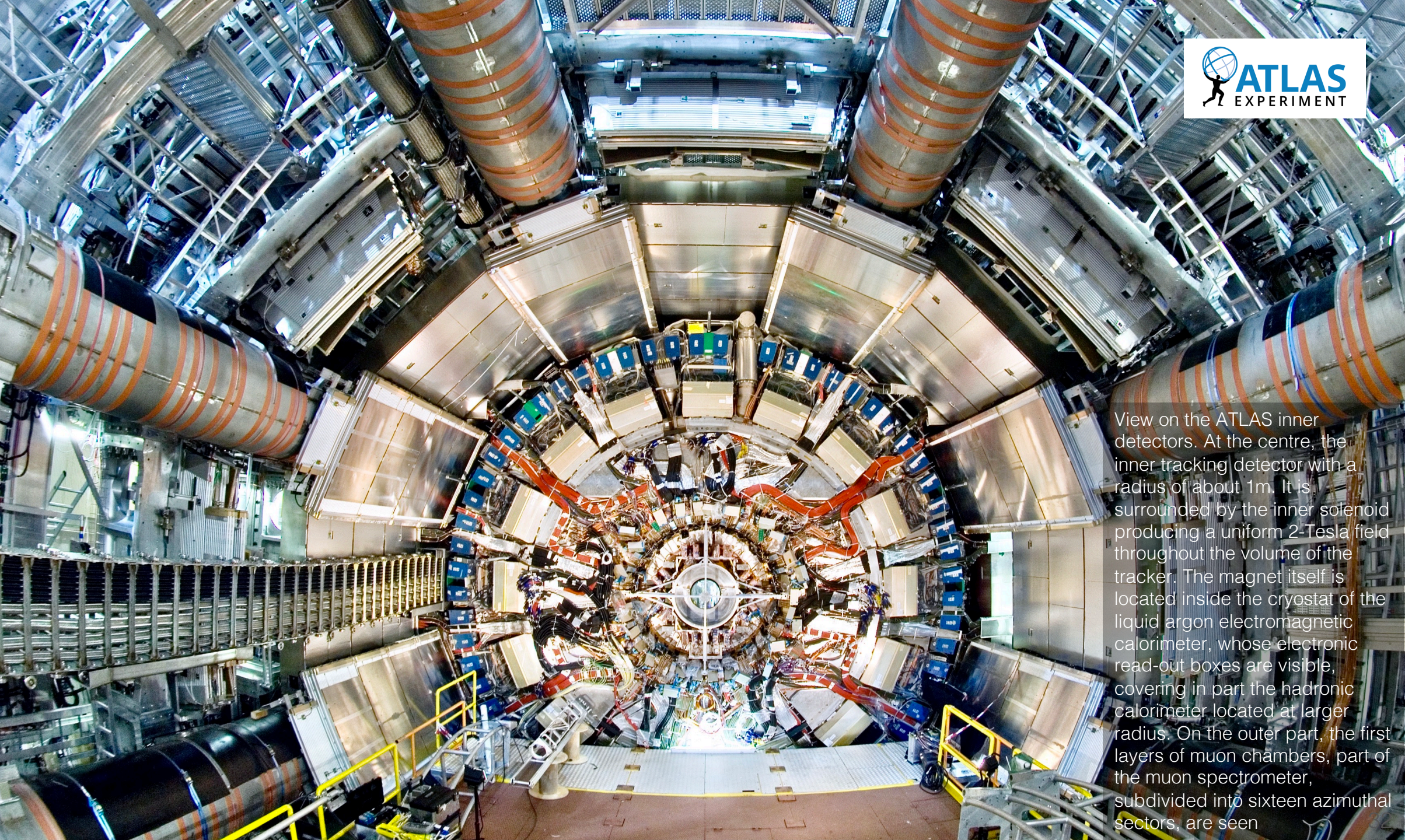
# ATLAS Detector construction and installation







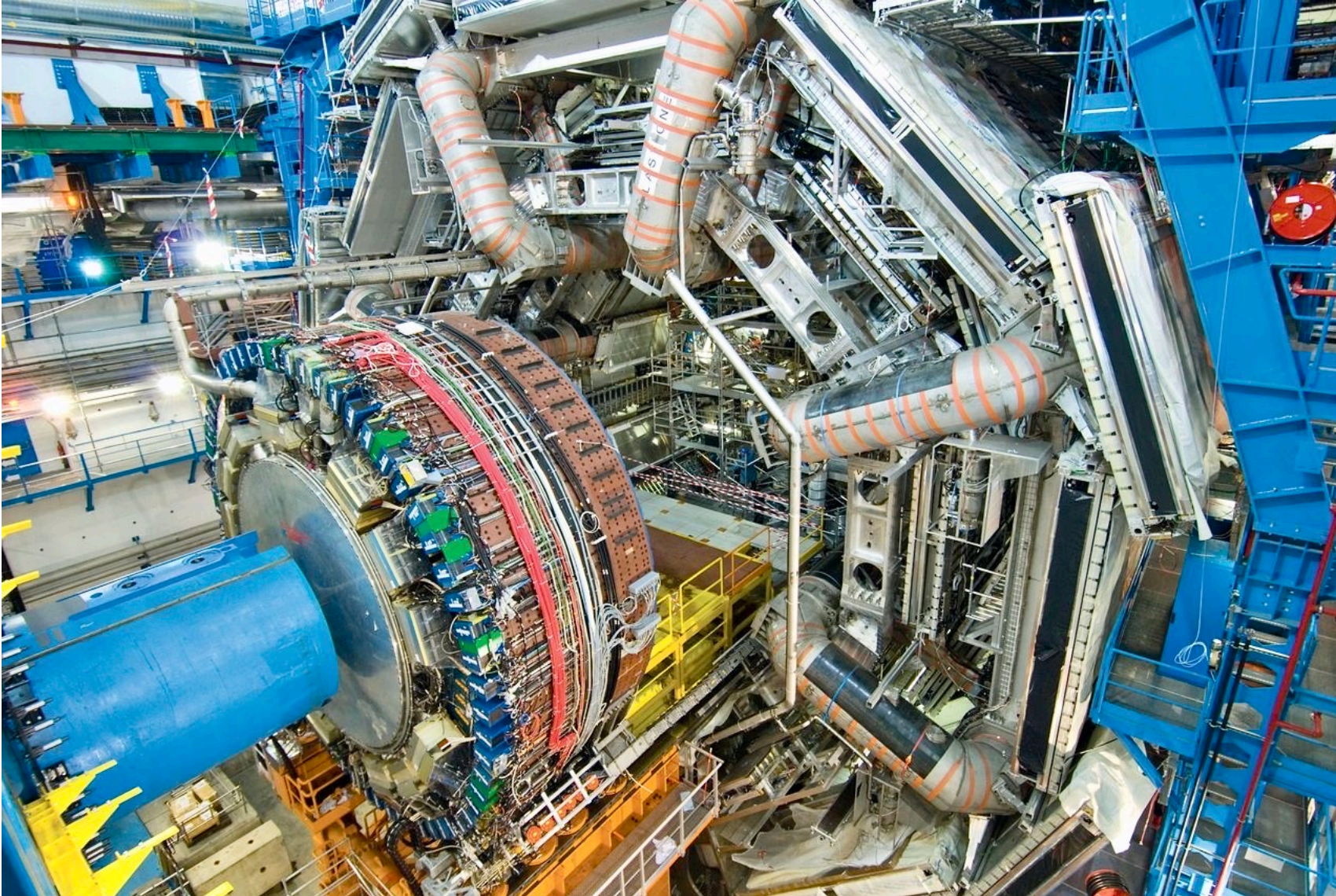




View on the ATLAS inner detectors. At the centre, the inner tracking detector with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic calorimeter, whose electronic read-out boxes are visible, covering in part the hadronic calorimeter located at larger radius. On the outer part, the first layers of muon chambers, part of the muon spectrometer, subdivided into sixteen azimuthal sectors, are seen

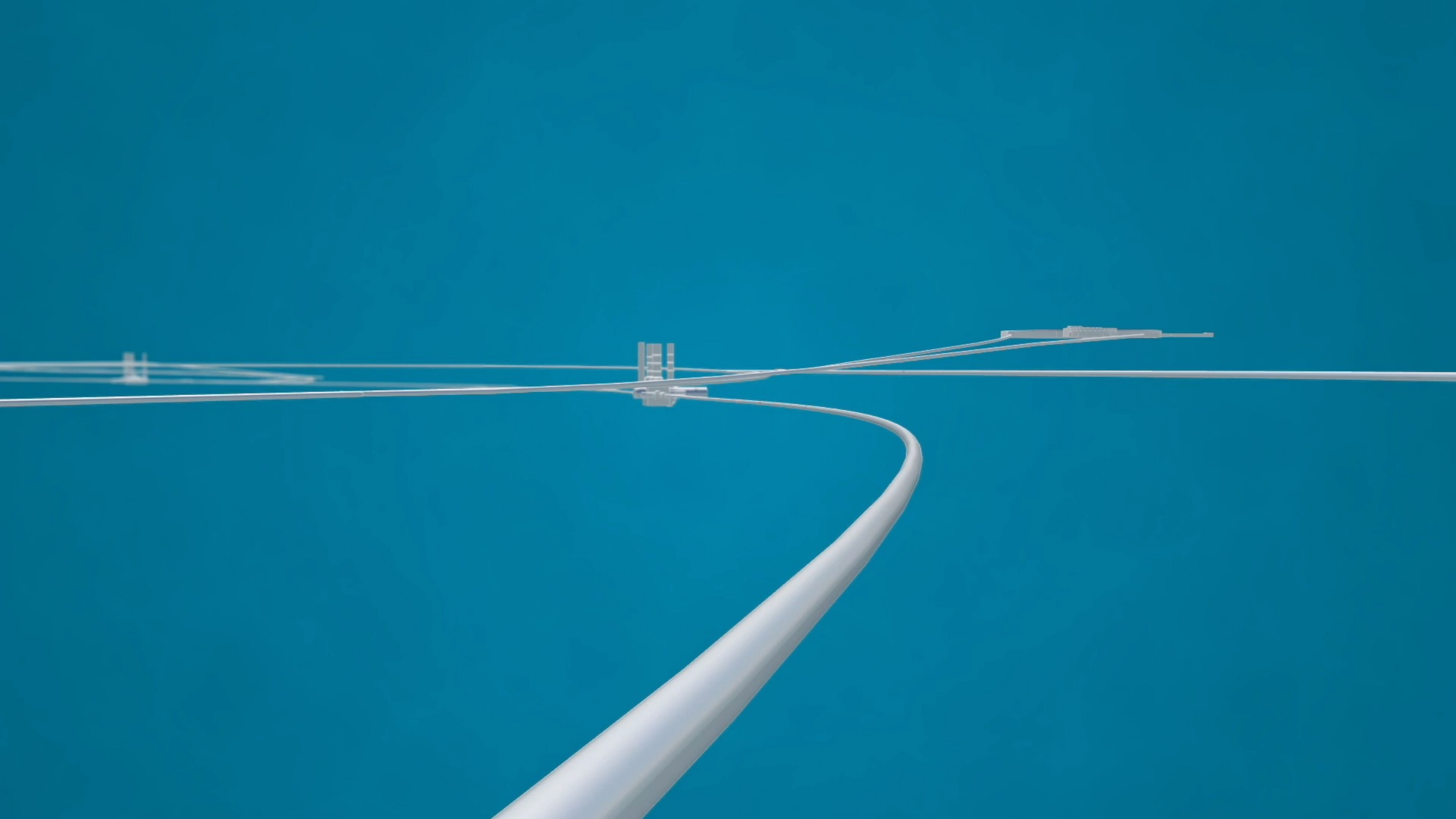


# ATLAS Detector construction and installation – Calorimeters



View of the central part of ATLAS during final assembly stages. The wire chambers mounted inside and around the toroid magnet cryostats are well visible, as is part of the end-cap hadronic calorimeter before its insertion inside the magnet







# Data analysis

**The analysis of the electronic detector data requires extremely sophisticated computer and mathematical algorithms as well as a deep understanding of statistics**

Particle physicists have developed and used machine learning algorithms long before it became ubiquitous in science and industry

High-speed internet and data replication to computer centres across the world allows ATLAS physicists all over the world to analyse the data and contribute to the scientific publications

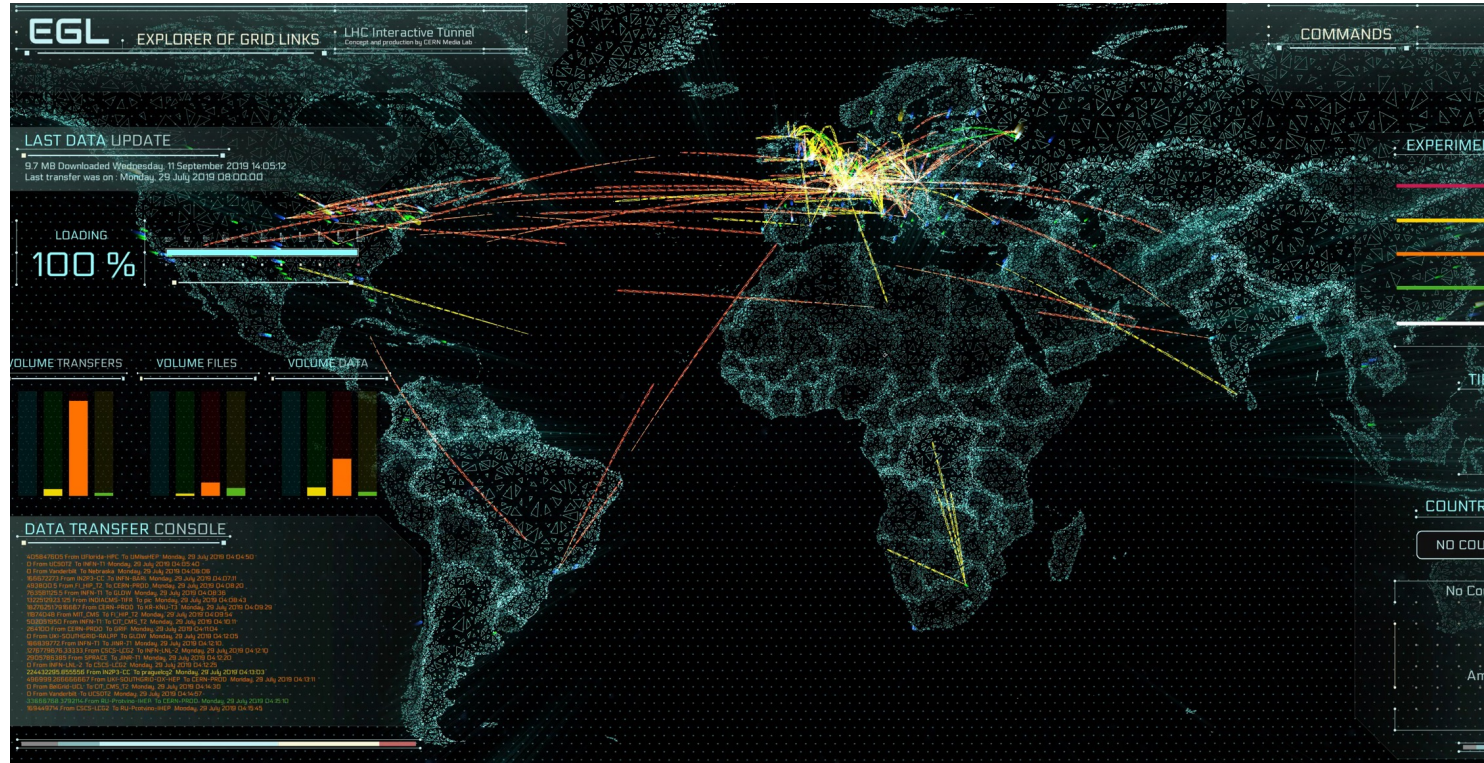




# The data processing relies on worldwide LHC Computing Grid



Used to store, distribute, process and analyse data

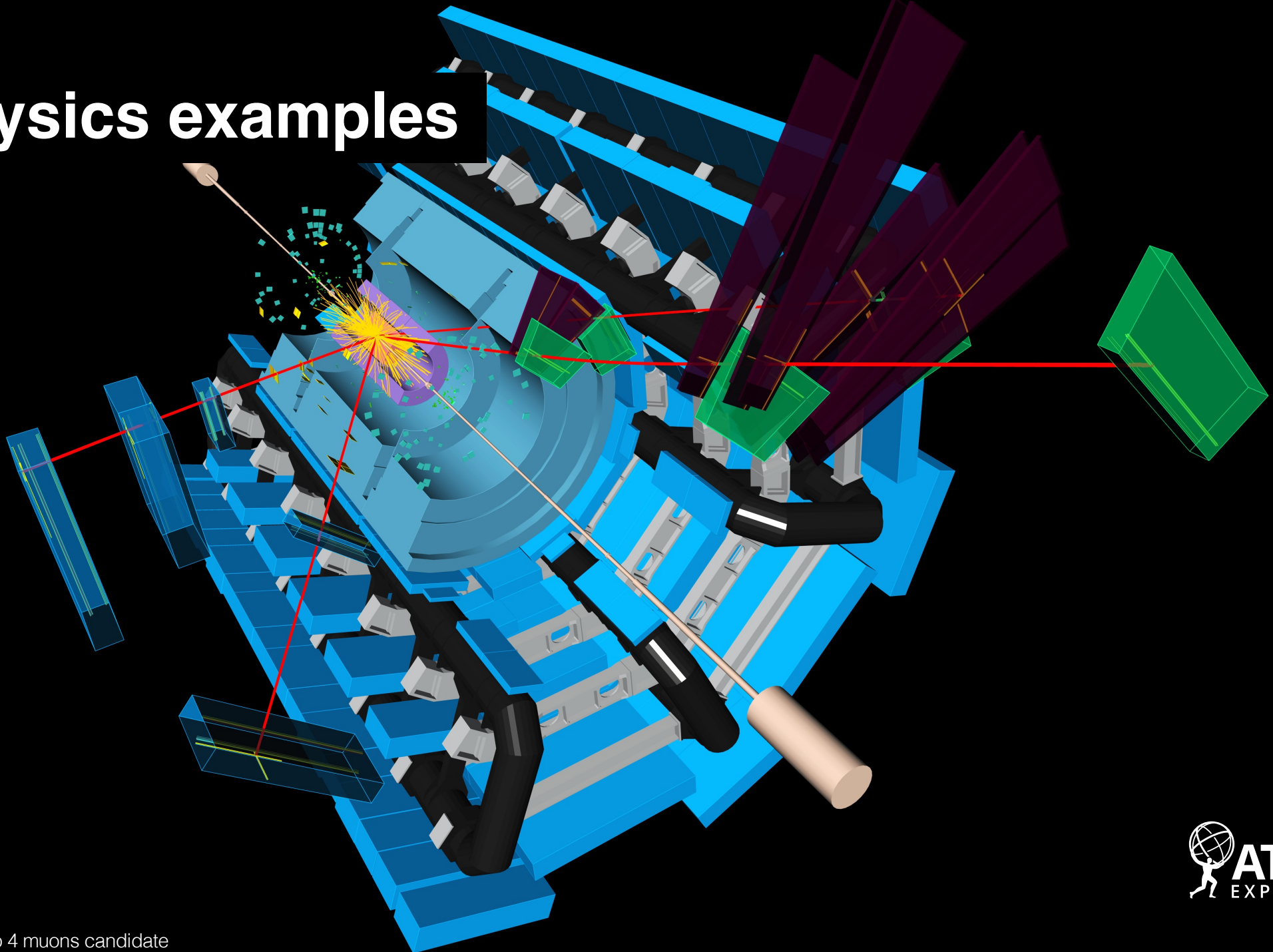


> 1 million processing cores in about 160 data centres in 42 countries

More than 1000 Petabytes of CERN data stored world-wide



# Physics examples

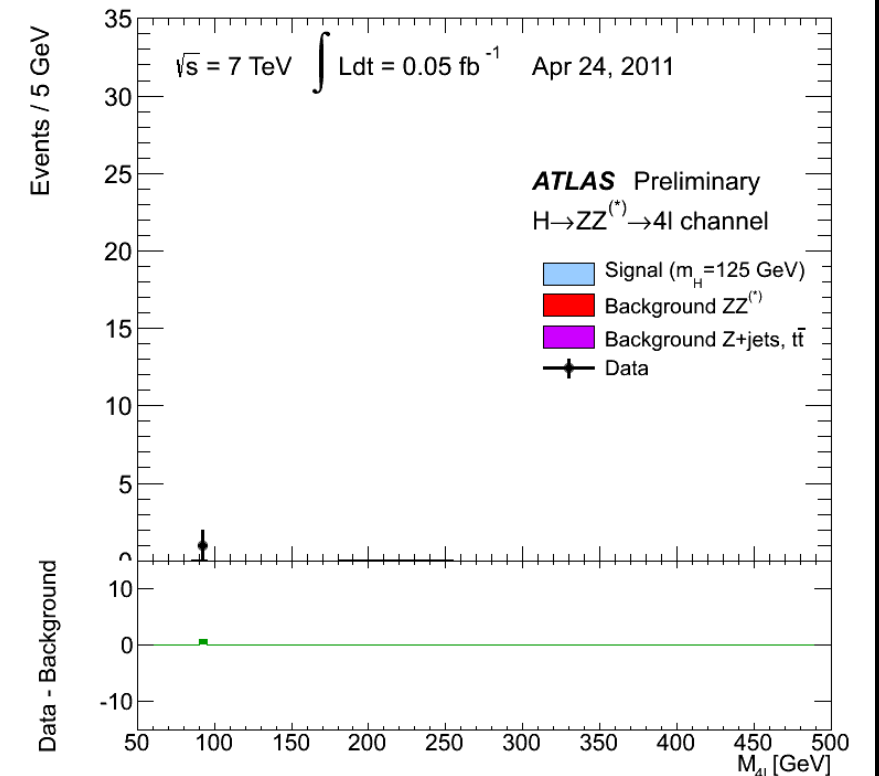




# 2012 Higgs boson discovery – 10 years ago !



Fabiola Gianotti and Peter Higgs, 4 July 2012





# 2012 Higgs boson discovery



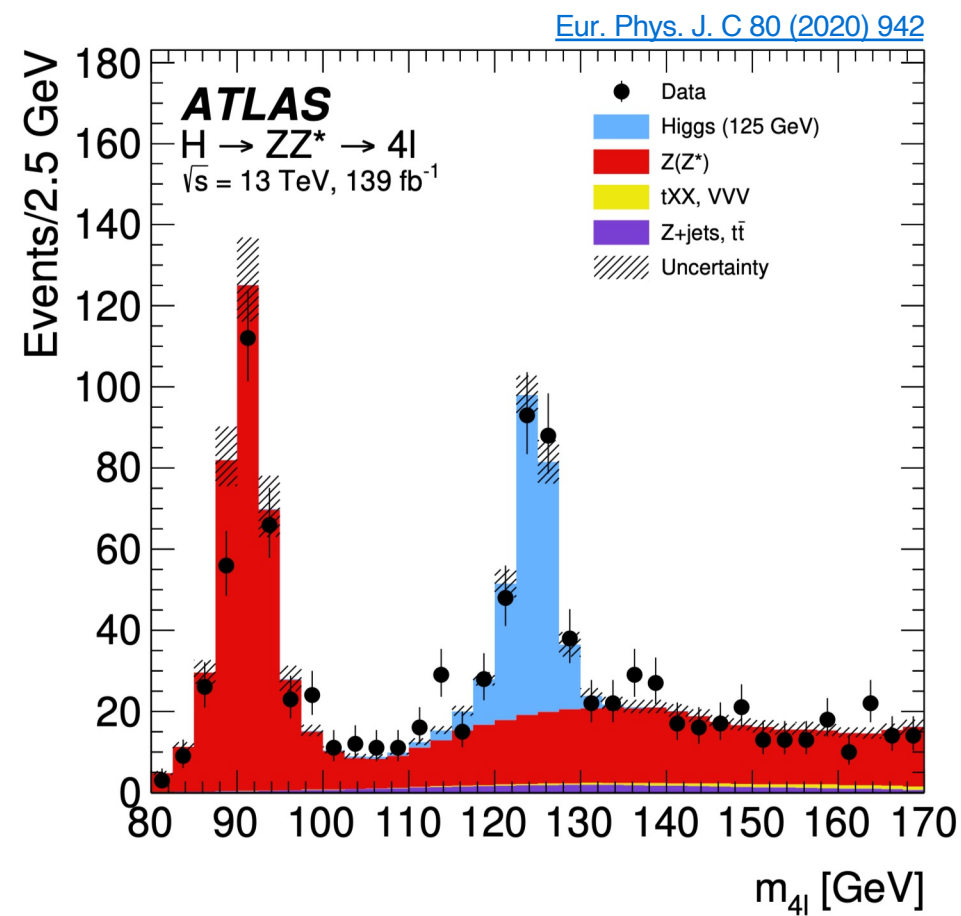
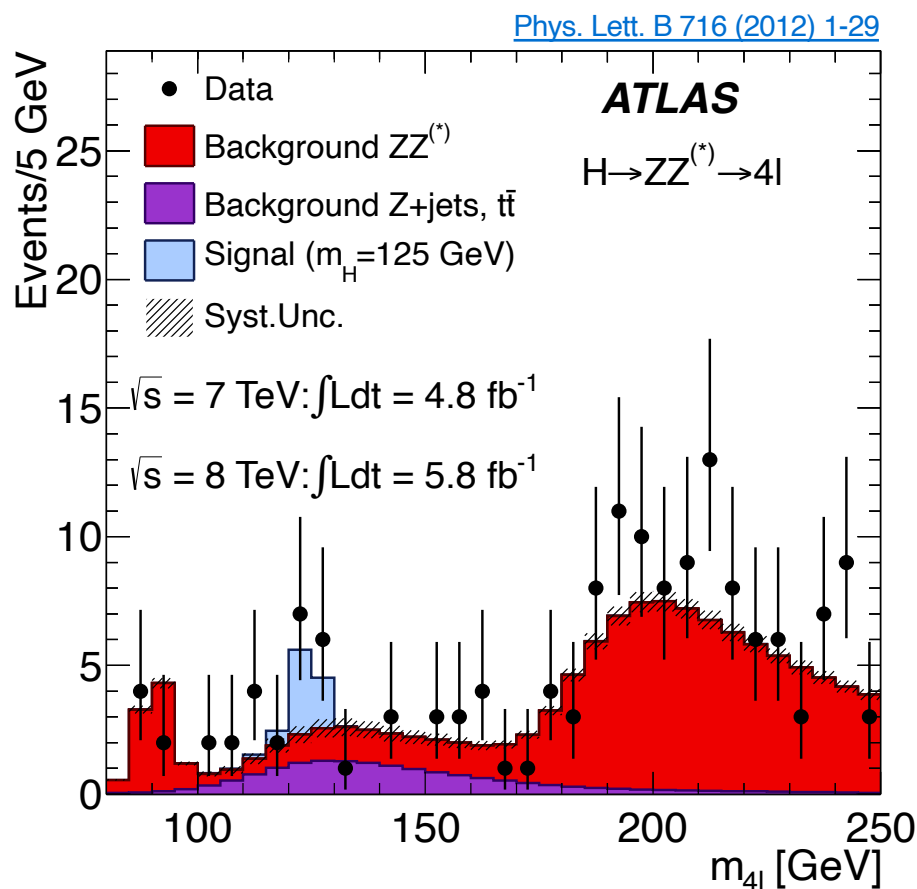
Nobel Prize in physics 2013 after Higgs boson discovery to the inventors of Higgs mechanism:  
**Peter Higgs and Francois Englert**

ATLAS and CMS physicists building at CERN after the announcement of Nobel Prize in October 2013

A Higgs boson to 4 muons candidate



# 2012 Higgs boson discovery — then and today





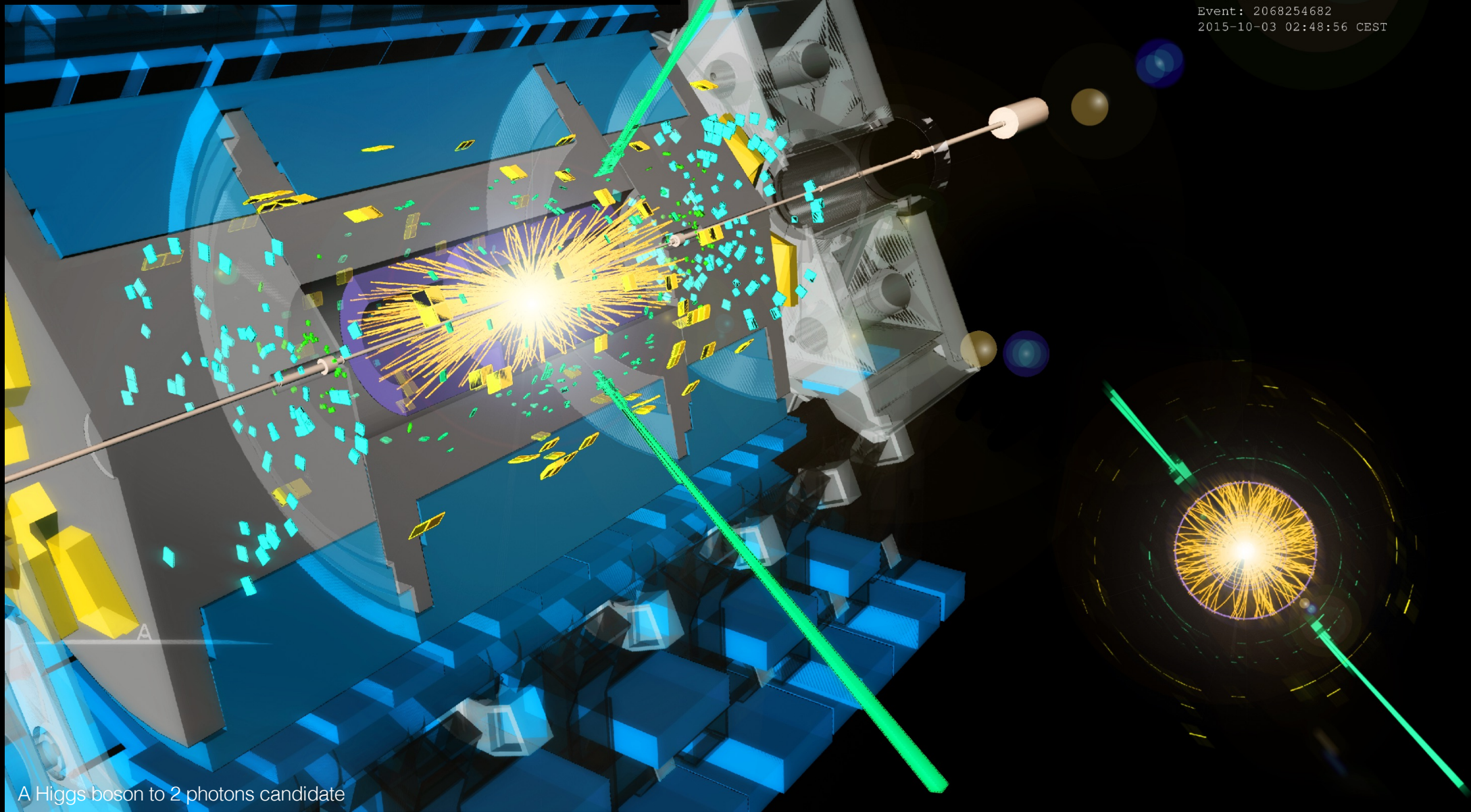
# More decay channels



Run: 280862

Event: 2068254682

2015-10-03 02:48:56 CEST



A Higgs boson to 2 photons candidate



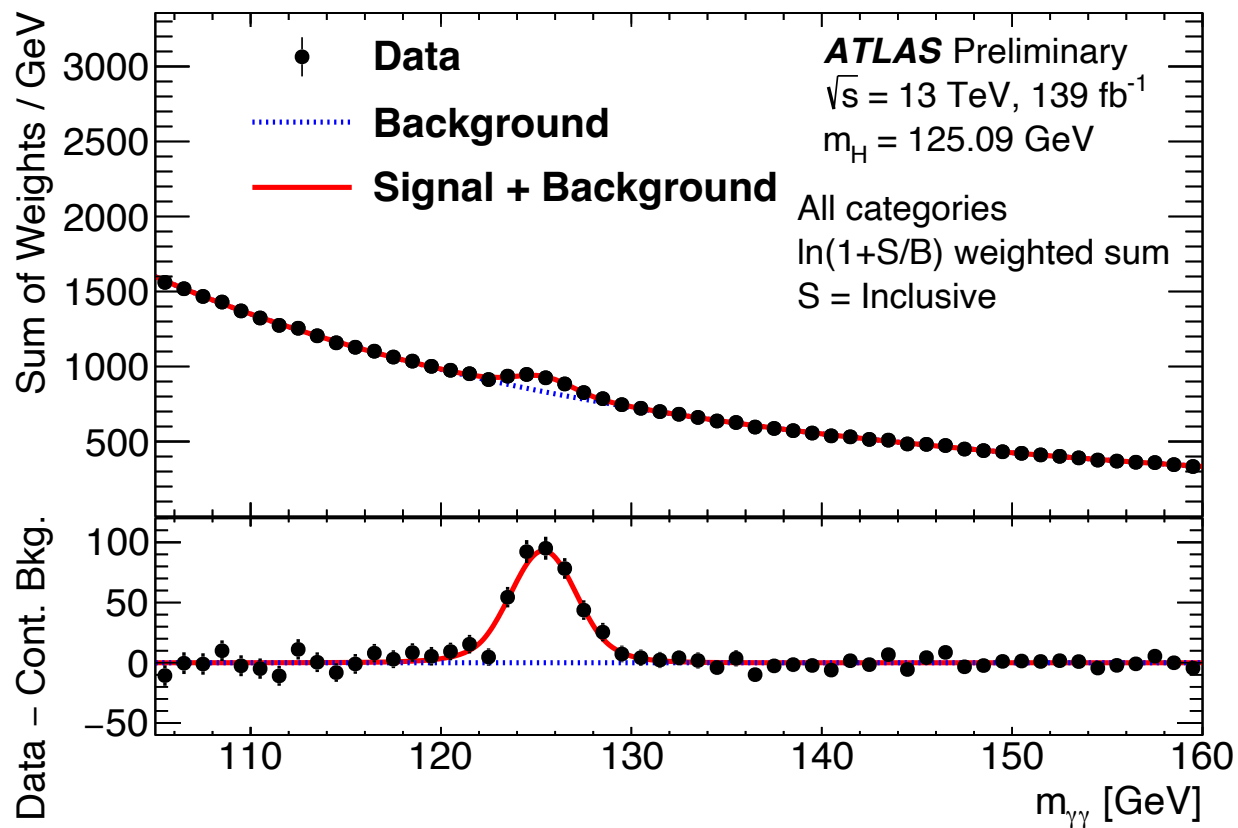
# More decay channels



Run: 280862

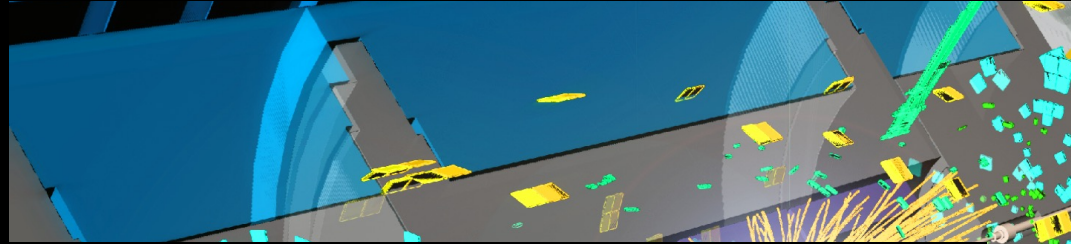
Event: 2068254682

2015-10-03 02:48:56 CEST



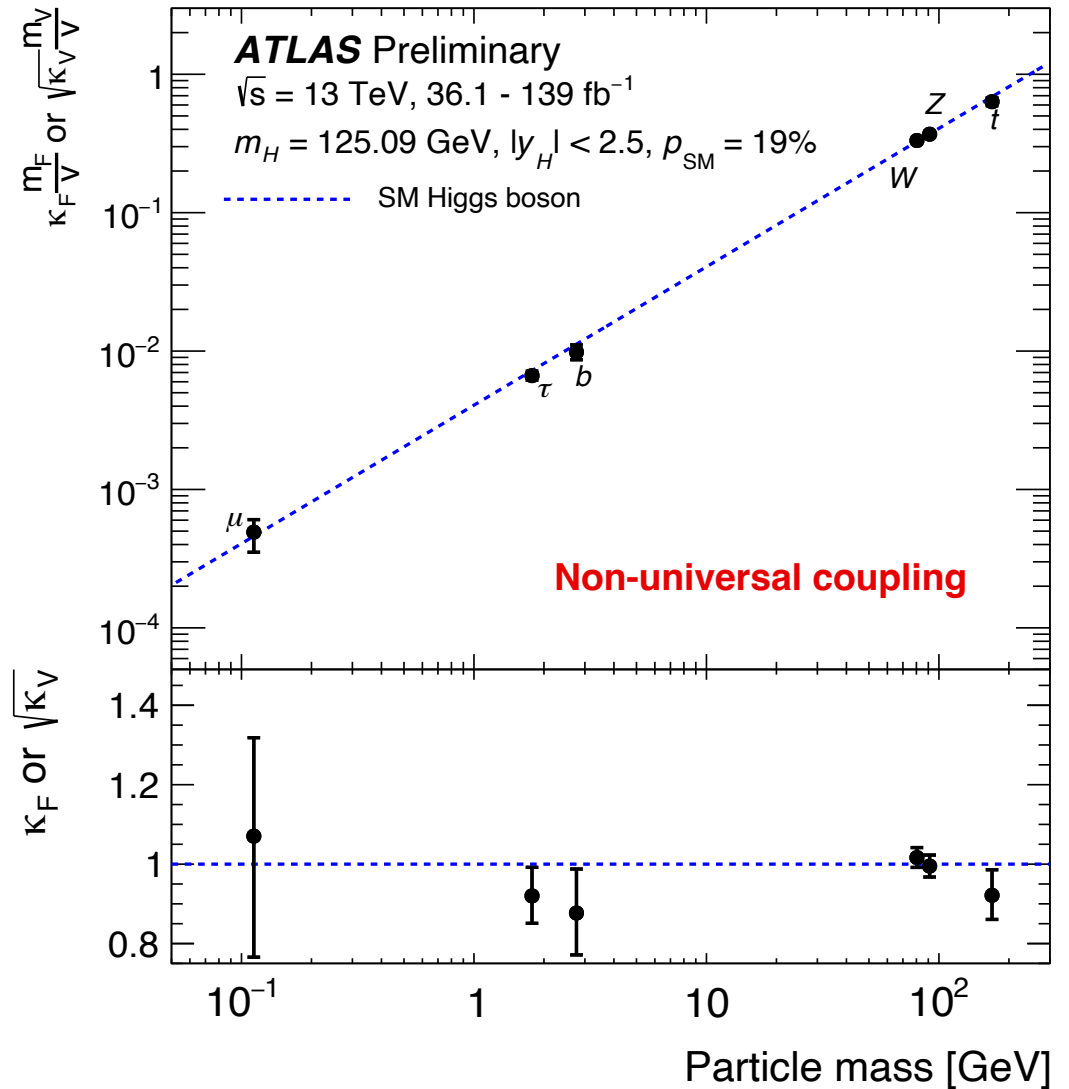
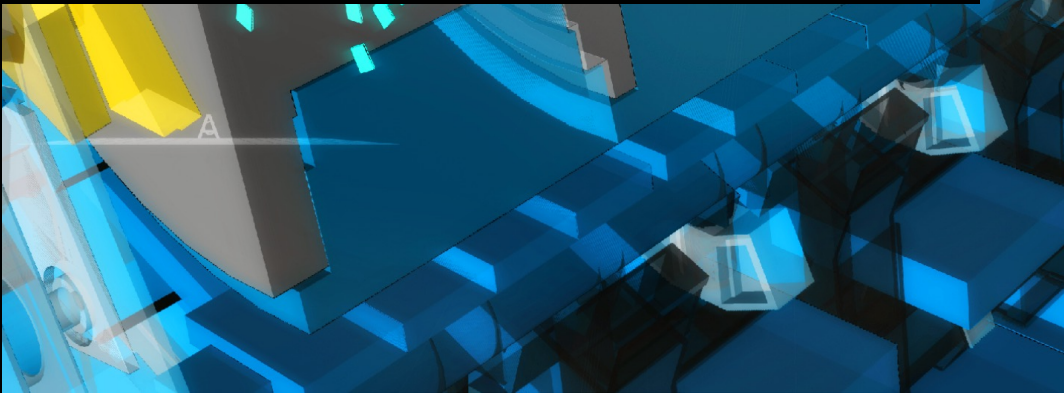


# The Higgs mechanism is real !



The Higgs sector is directly connected with very profound questions: naturalness, vacuum stability & energy, flavour

The Higgs boson discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades



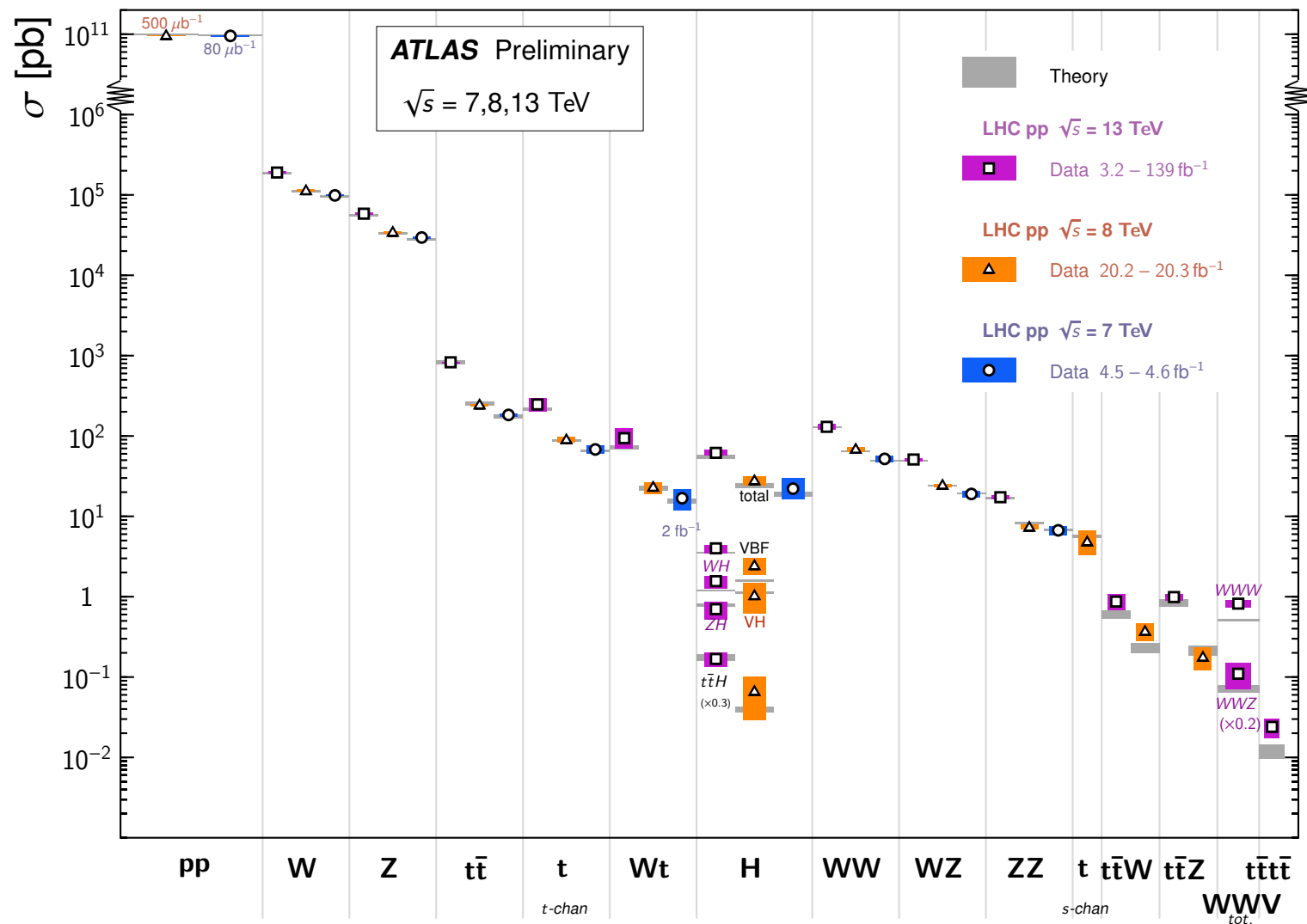


**ATLAS discovered  
numerous processes  
never observed before**



# Standard Model Total Production Cross Section Measurements

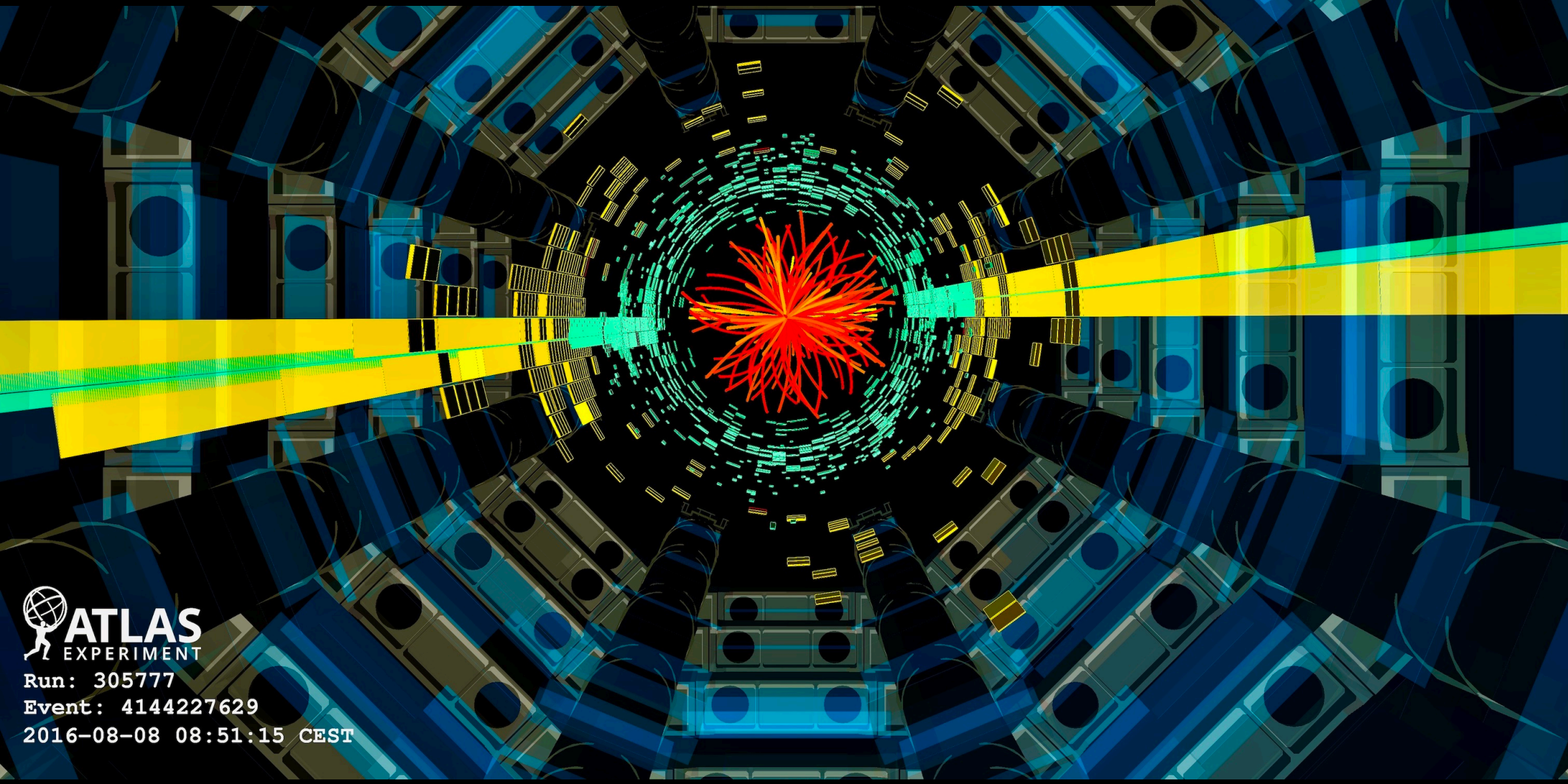
Status: February 2022



A harvest of unique measurements probing new forms of particle interactions and very rare processes



# Deep searches for new phenomena



 **ATLAS**  
EXPERIMENT

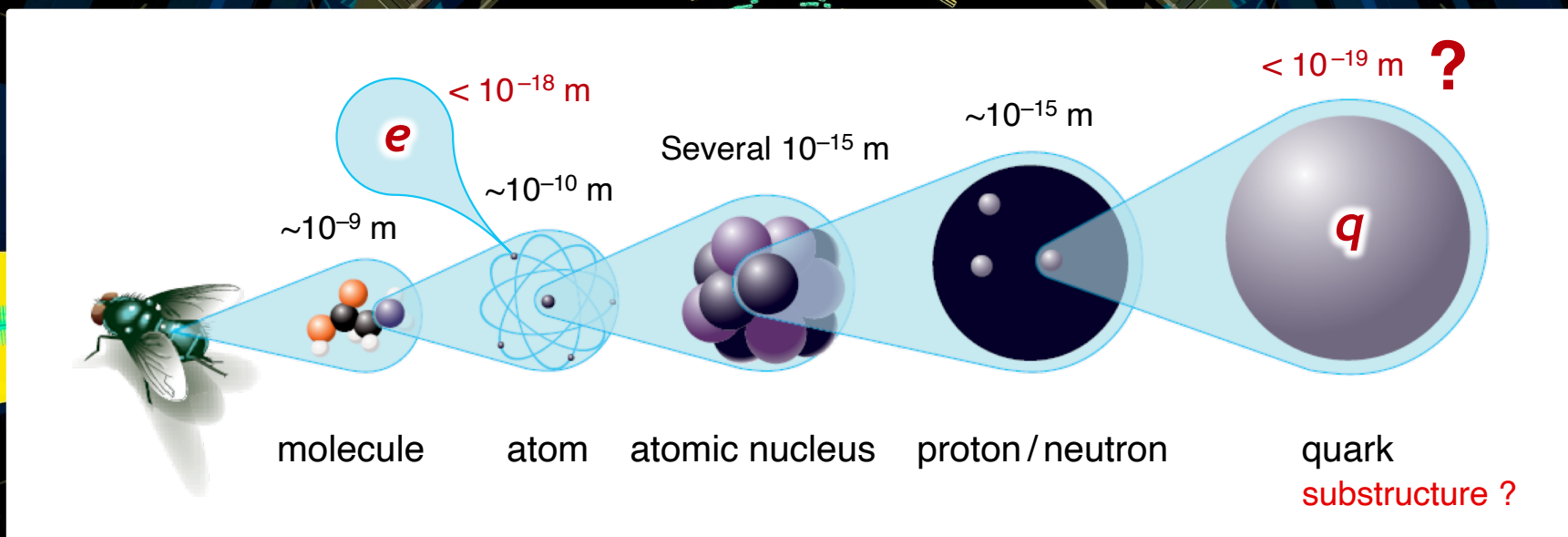
Run: 305777

Event: 4144227629

2016-08-08 08:51:15 CEST

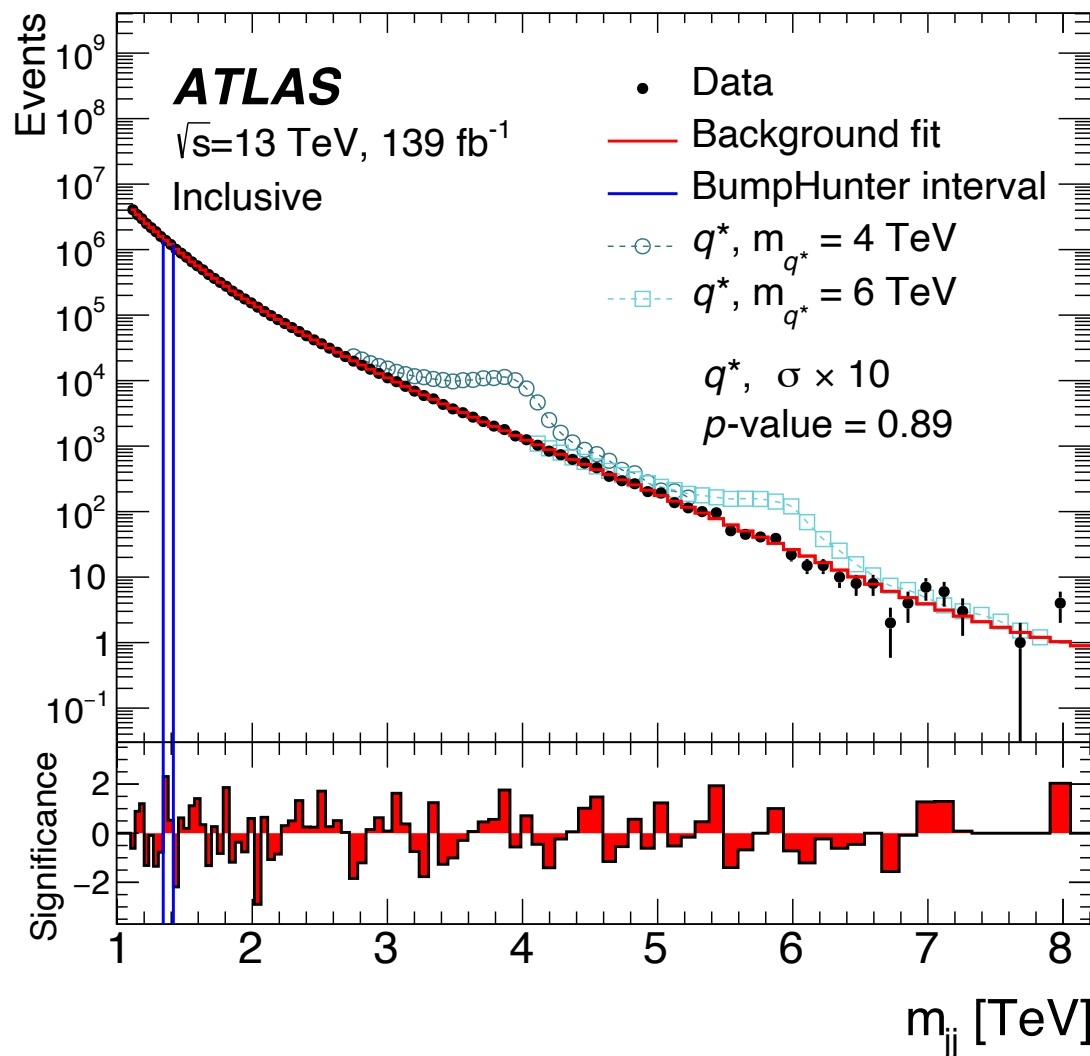


# Are quarks elementary particles?





# Are quarks elementary particles?





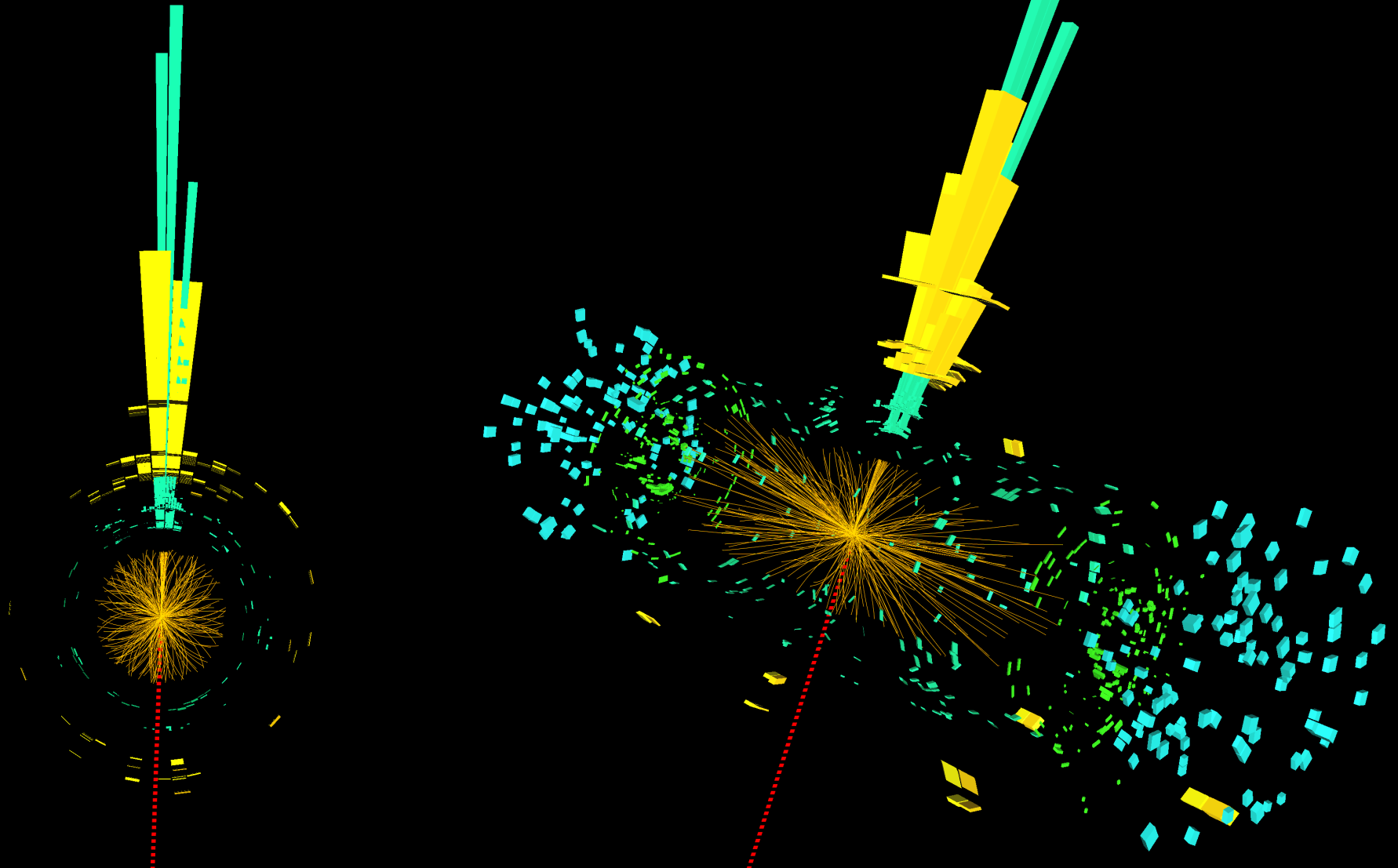
**Could gravity  
be strong in  
extra spatial  
dimensions?**



**ATLAS**  
EXPERIMENT

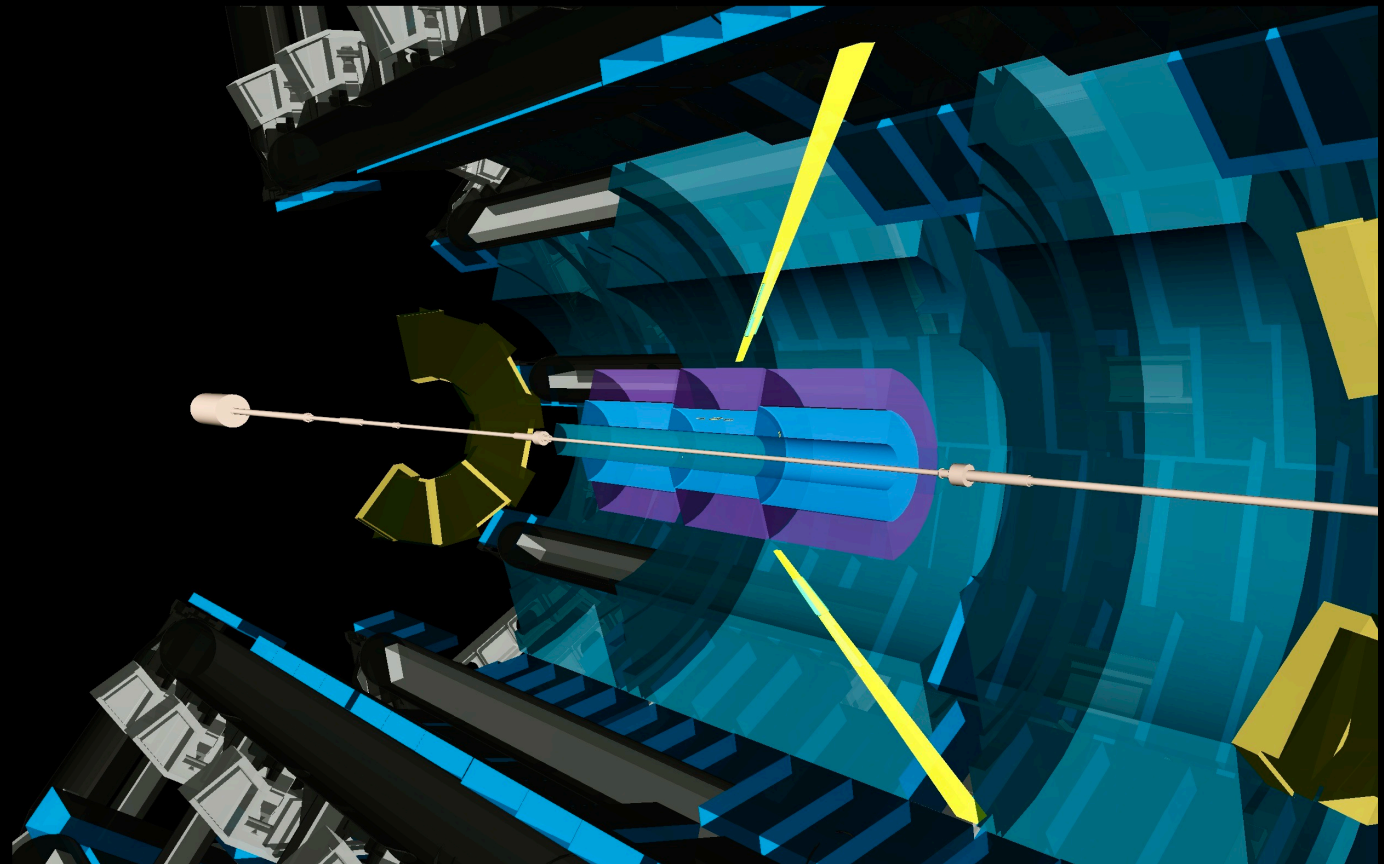
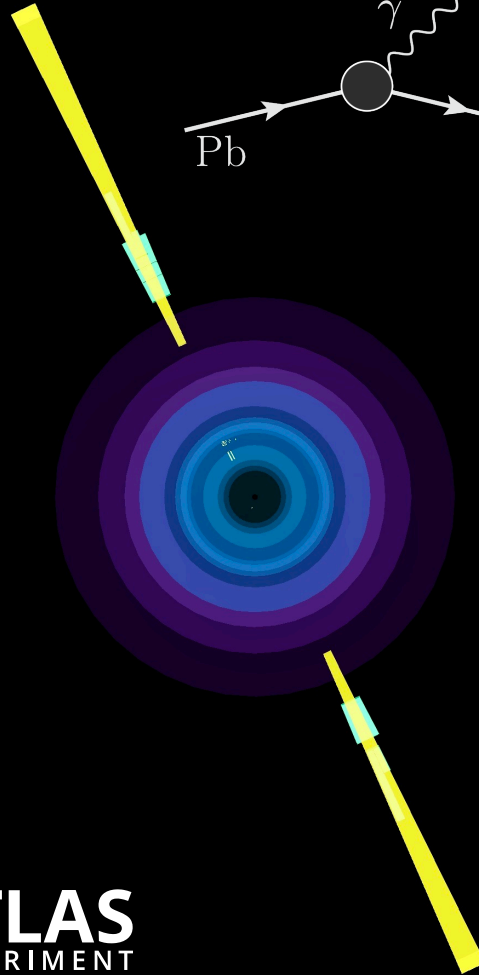
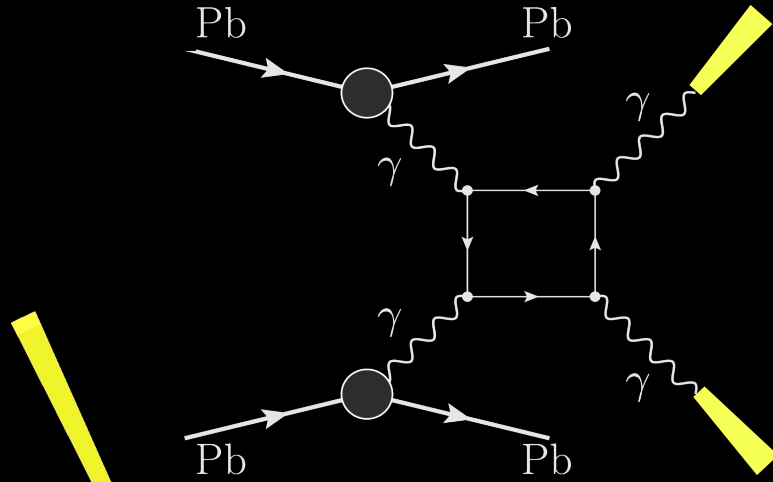


# Are dark matter particles produced at the LHC ?





**Do we understand the  
interaction of light in  
extreme electromagnetic  
fields ?**





Many questions remain, of which many can be tackled at the LHC

# The next steps

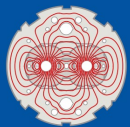


# Preparing the future — the grand plan





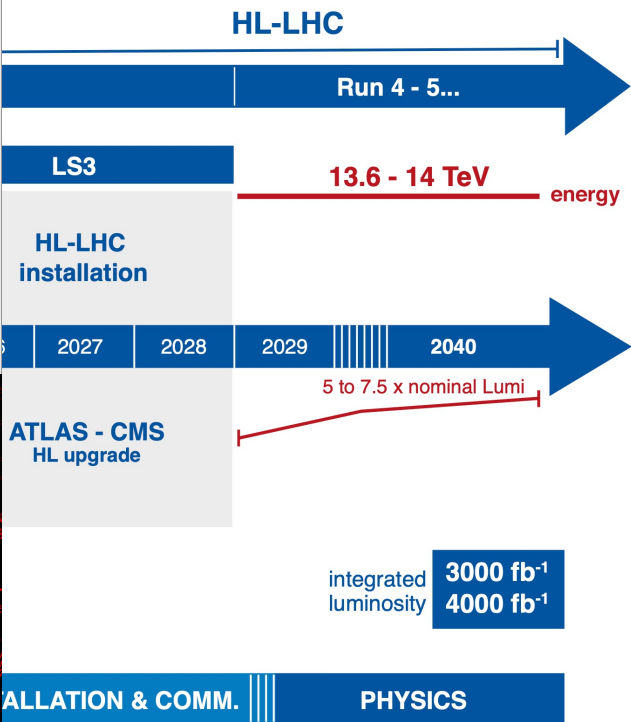
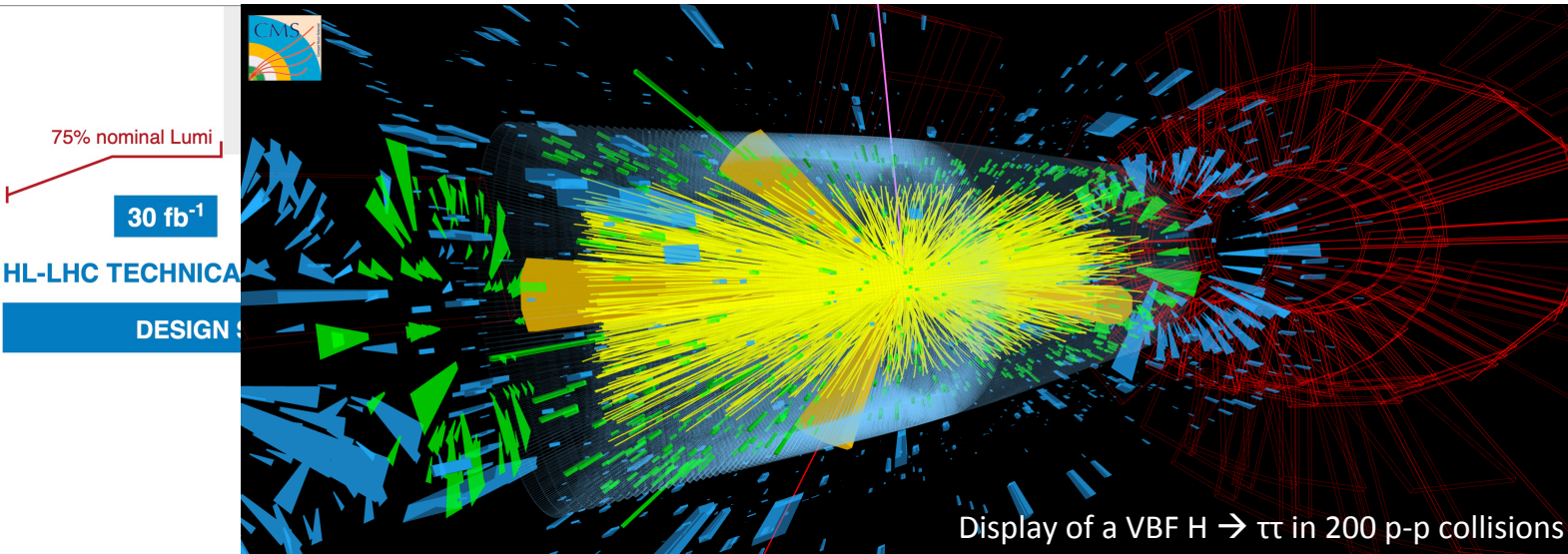
# Preparing the future — the grand plan



## LHC / HL-LHC Plan

### High Luminosity LHC (starting 2029)

- Higgs factory (400M Higgs bosons produced) for precise Higgs coupling ratio measurements, and increased overall rare & new physics sensitivity
- Large-scale detector upgrades required for improved robustness against pileup and radiation





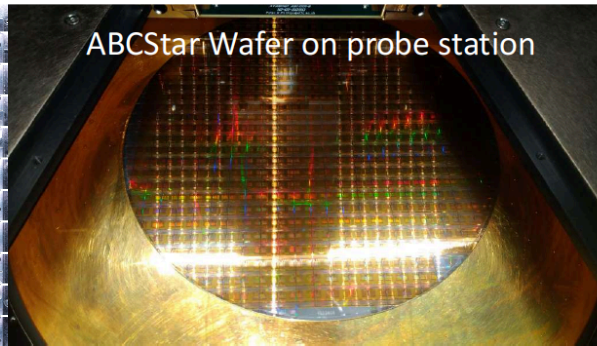
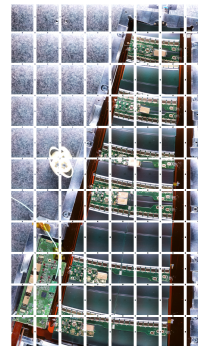
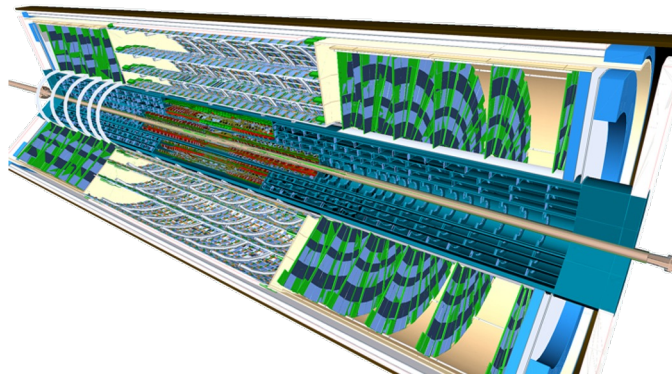
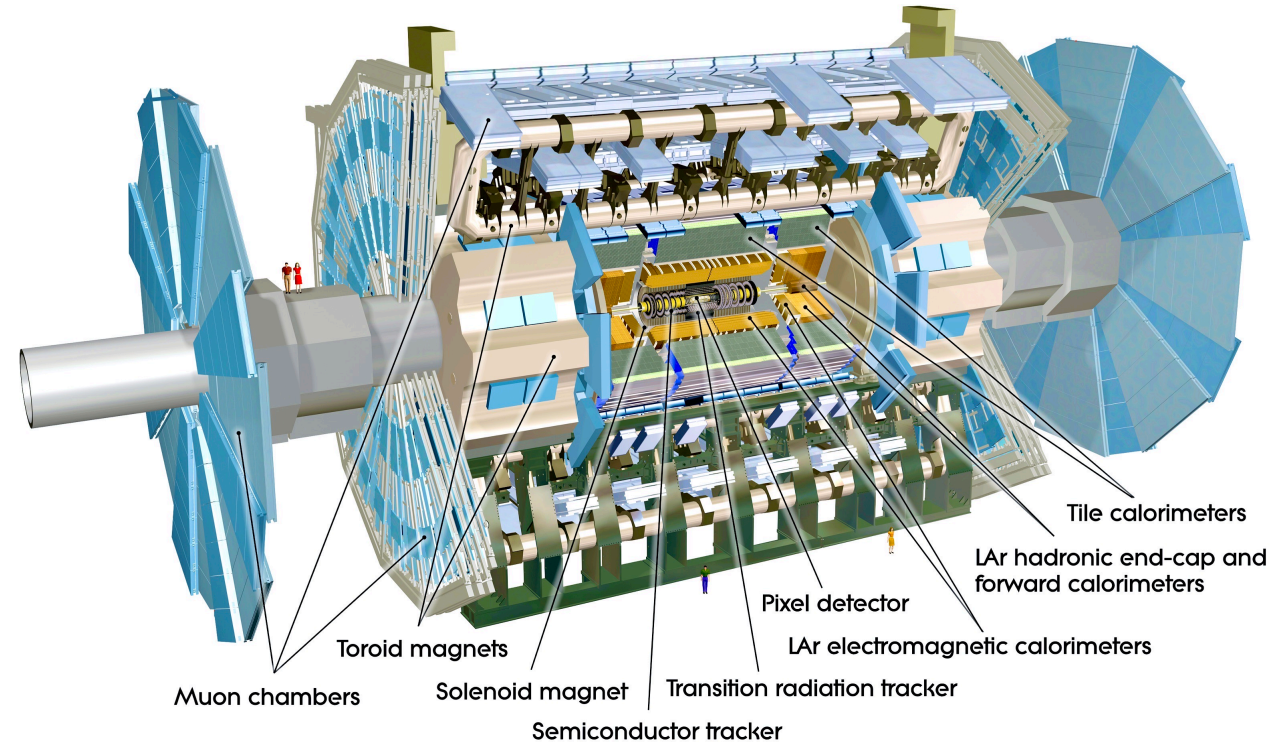
# High-Luminosity LHC (HL-LHC)



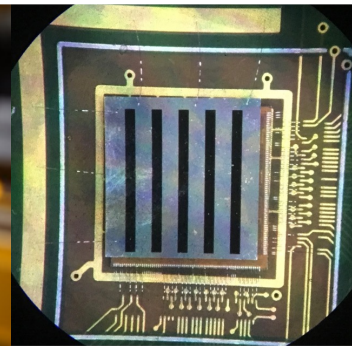
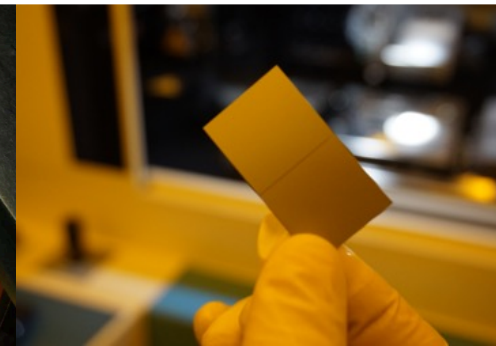
The HL-LHC promises 20 times the data sample currently collected

Its beam intensity requires unprecedented detector and computing technologies:

- Radiation hardness
- High detection granularity and resolution
- Precise timing detectors
- Machine learning & data science
- High-performance computing



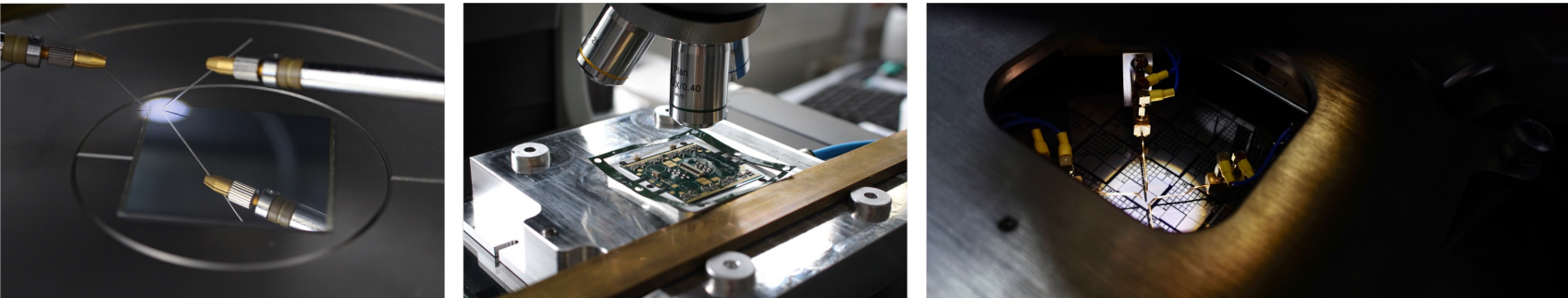
ABCStar Wafer on probe station





# Detector upgrades for the HL-LHC

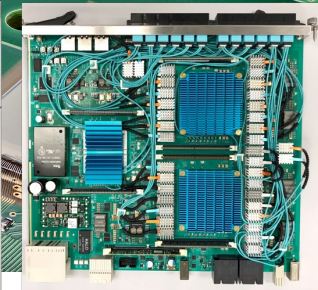
Pixel bare module probing and module metrology (Göttingen)



sMDT geometry measurement (MPI)



TDAQ  
GCM  
prototype  
(BNL)



ITk Strip petal (SFU & TRIUMF)



HGTD testbeam at DESY



sMDT chamber measurement (MPI)

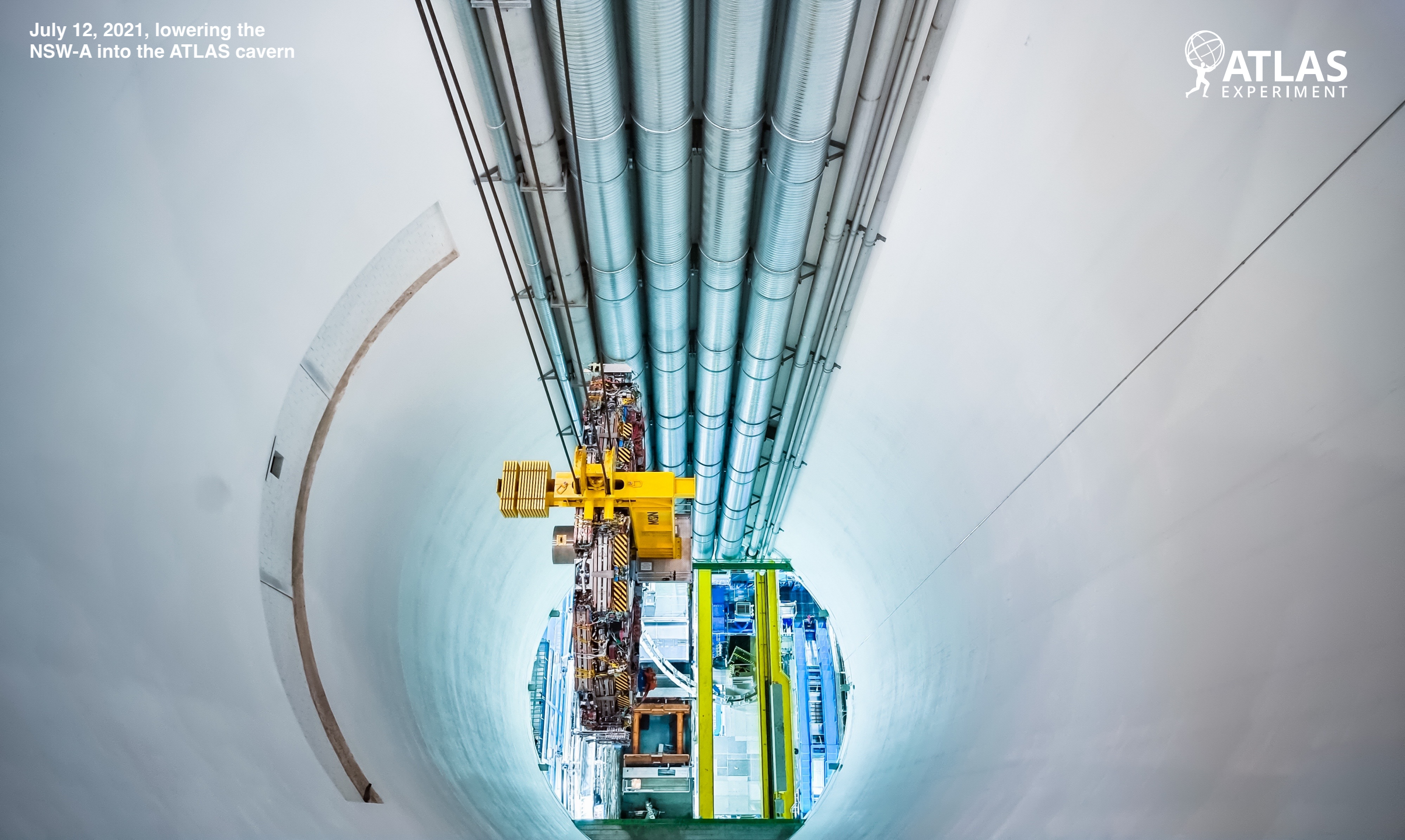


# Detector upgrades for the HL-LHC



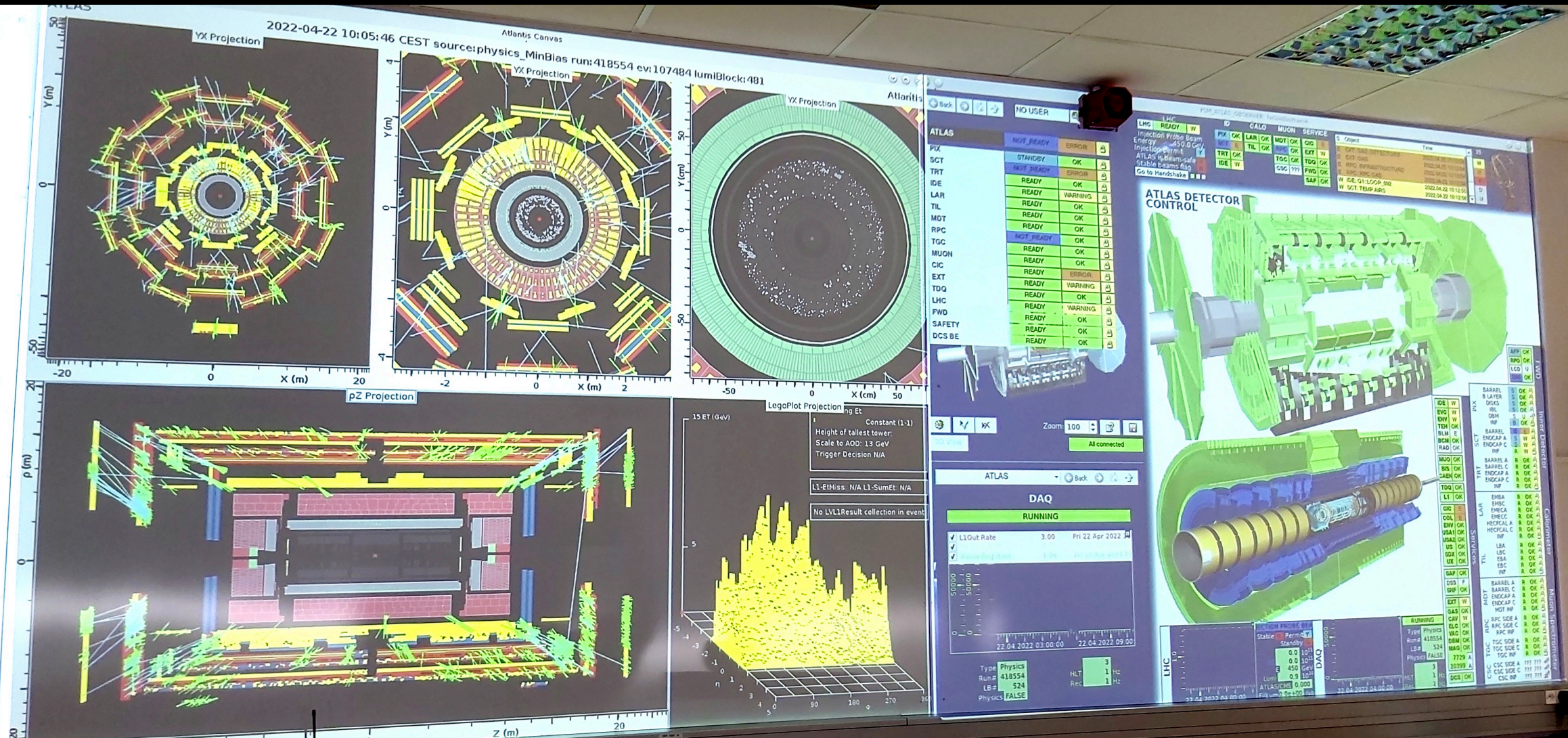


July 12, 2021, lowering the  
NSW-A into the ATLAS cavern





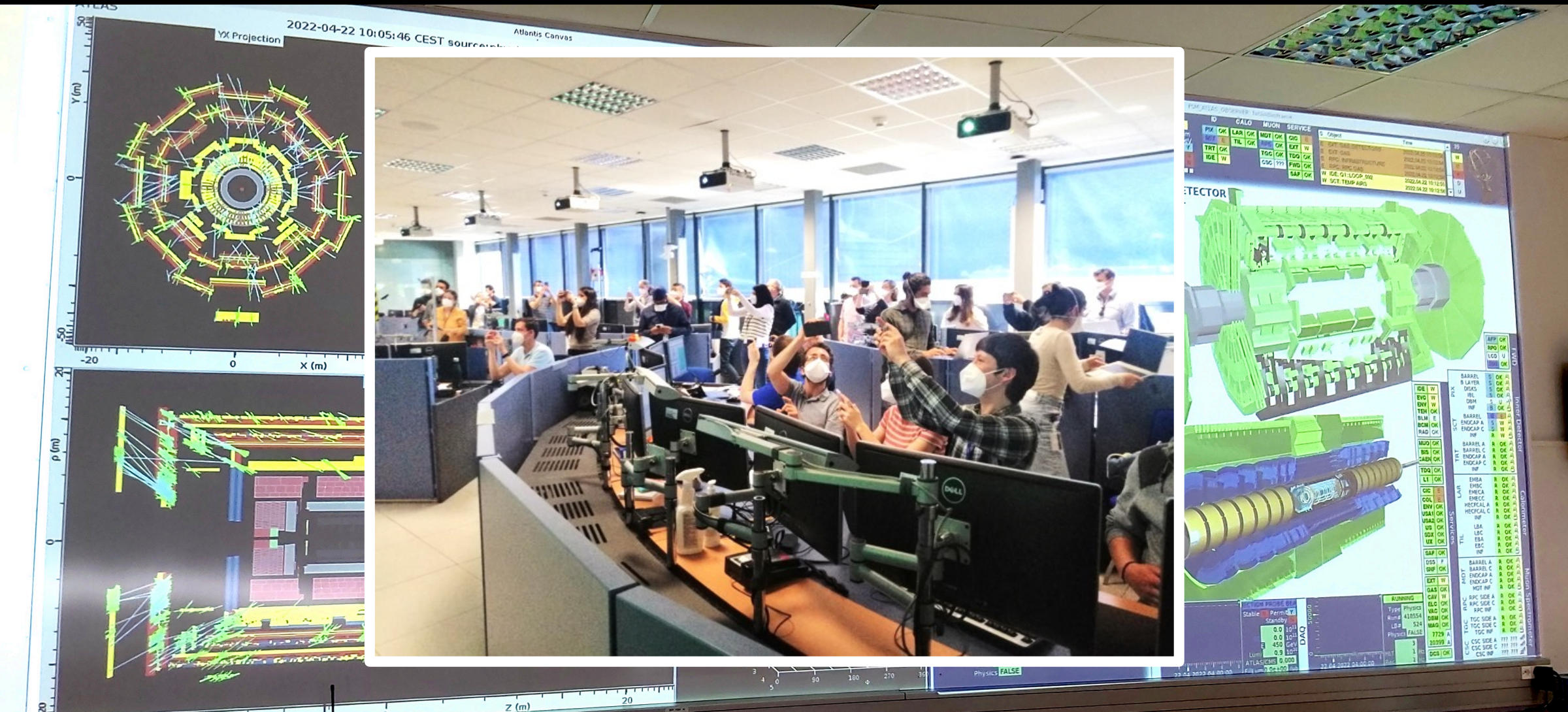
# Begin of Run 3 commissioning on 22 April 2022



Splash view from the ATLAS Control Room on 22 Apr 2022



# Begin of Run 3 commissioning on 22 April 2022



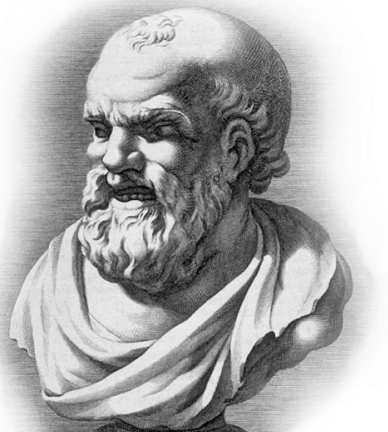
Splash view from the ATLAS Control Room on 22 Apr 2022



# Begin of Run 3 commissioning on 22 April 2022



We've come a long way —  
the adventure continues

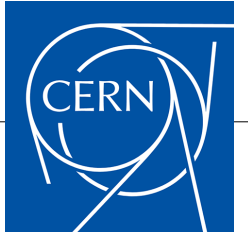




Extra slides







## 23 Member States

Austria – Belgium – Bulgaria – Czech Republic  
Denmark – Finland – France – Germany – Greece  
Hungary – Israel – Italy – Netherlands – Norway  
Poland – Portugal – Romania – Serbia – Slovakia  
Spain – Sweden – Switzerland – United Kingdom

## 3 Associates Member States in the pre-stage to membership

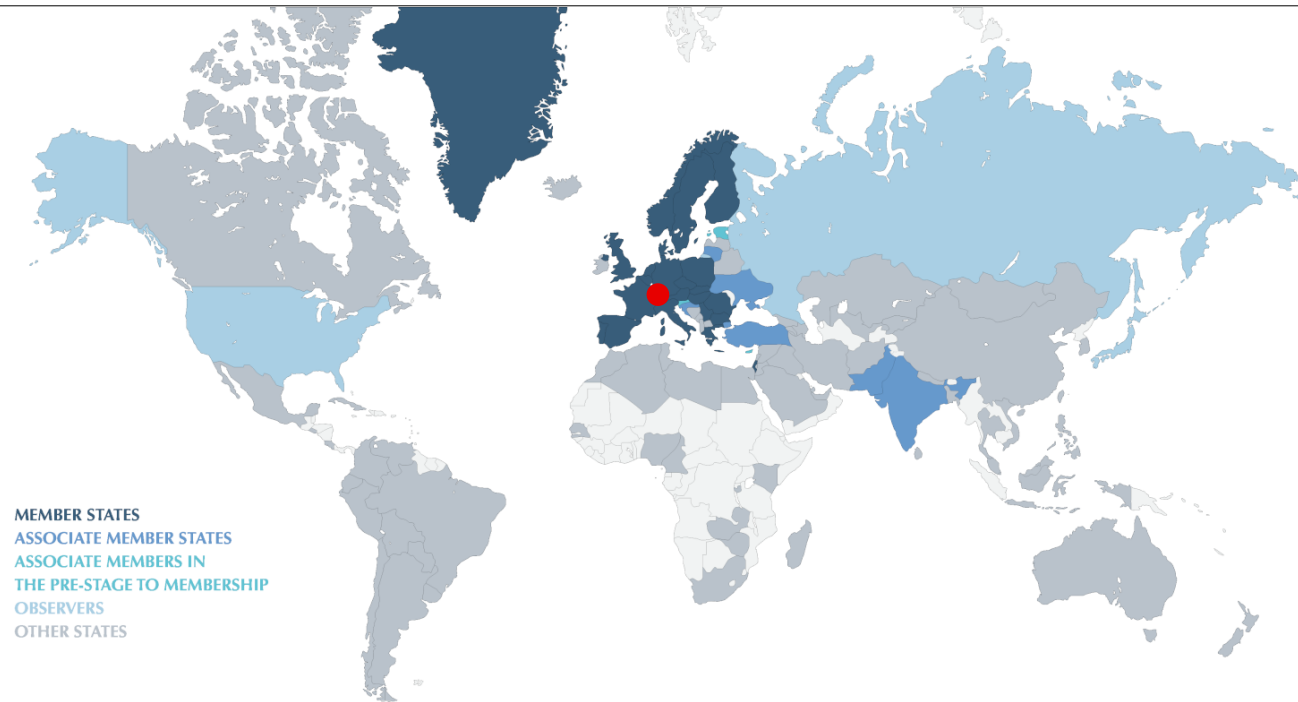
Cyprus – Estonia – Slovenia

## 6 Associate Member States

Croatia – India – Lithuania – Pakistan –  
Turkey – Ukraine

## 6 Observers

Japan – Russia – USA  
European Union – JINR – UNESCO



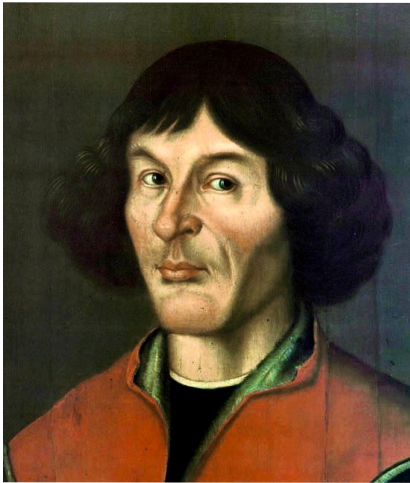
## More than 50 Cooperation Agreements with non-Member States and Territories

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia  
Bosnia and Herzegovina – Brazil – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Iceland  
Iran – Jordan – Kazakhstan – Latvia – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal  
New Zealand – North Macedonia – Palestine – Paraguay – People's Republic of China – Peru – Philippines – Qatar  
Republic of Korea – Saudi Arabia – Sri Lanka – South Africa – Thailand – Tunisia – United Arab Emirates – Vietnam

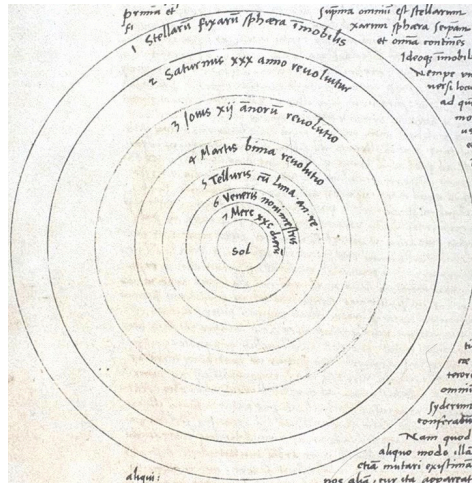


# Setting the stage

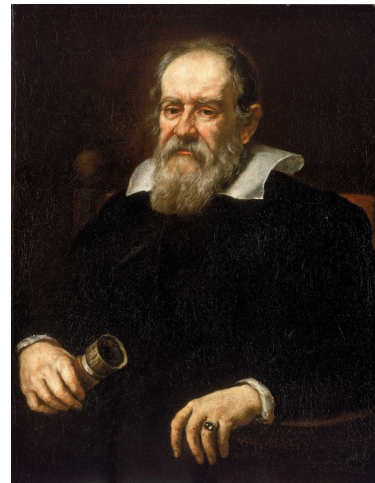
The scientific revolution began with **Nicolaus Copernicus** in the 16<sup>th</sup> century, shifting paradigms from the Ptolemaic model of the heavens to the heliocentric one, continued with **Galileo Galilei** and his *Dialogue Concerning the Two Chief World Systems* (1632), to find its culmination and accomplishment with the 1687 publication of **Isaac Newton's** *Philosophiæ Naturalis Principia Mathematica*, laying the foundations of modern mathematical physics



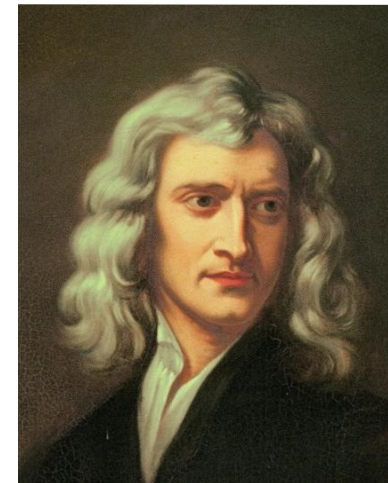
N. Copernicus (1473–1543)



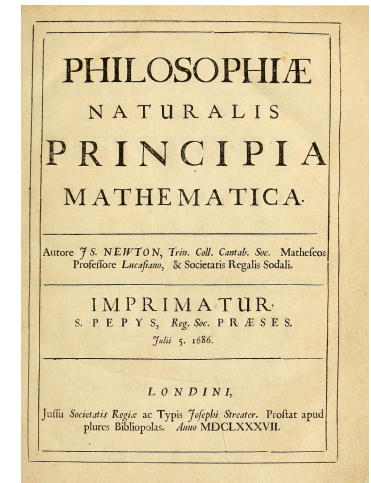
*On the Revolutions of the Celestial Spheres*, published in 1543



Galileo Galilei (1564–1642)



Isaac Newton (1642–1726)



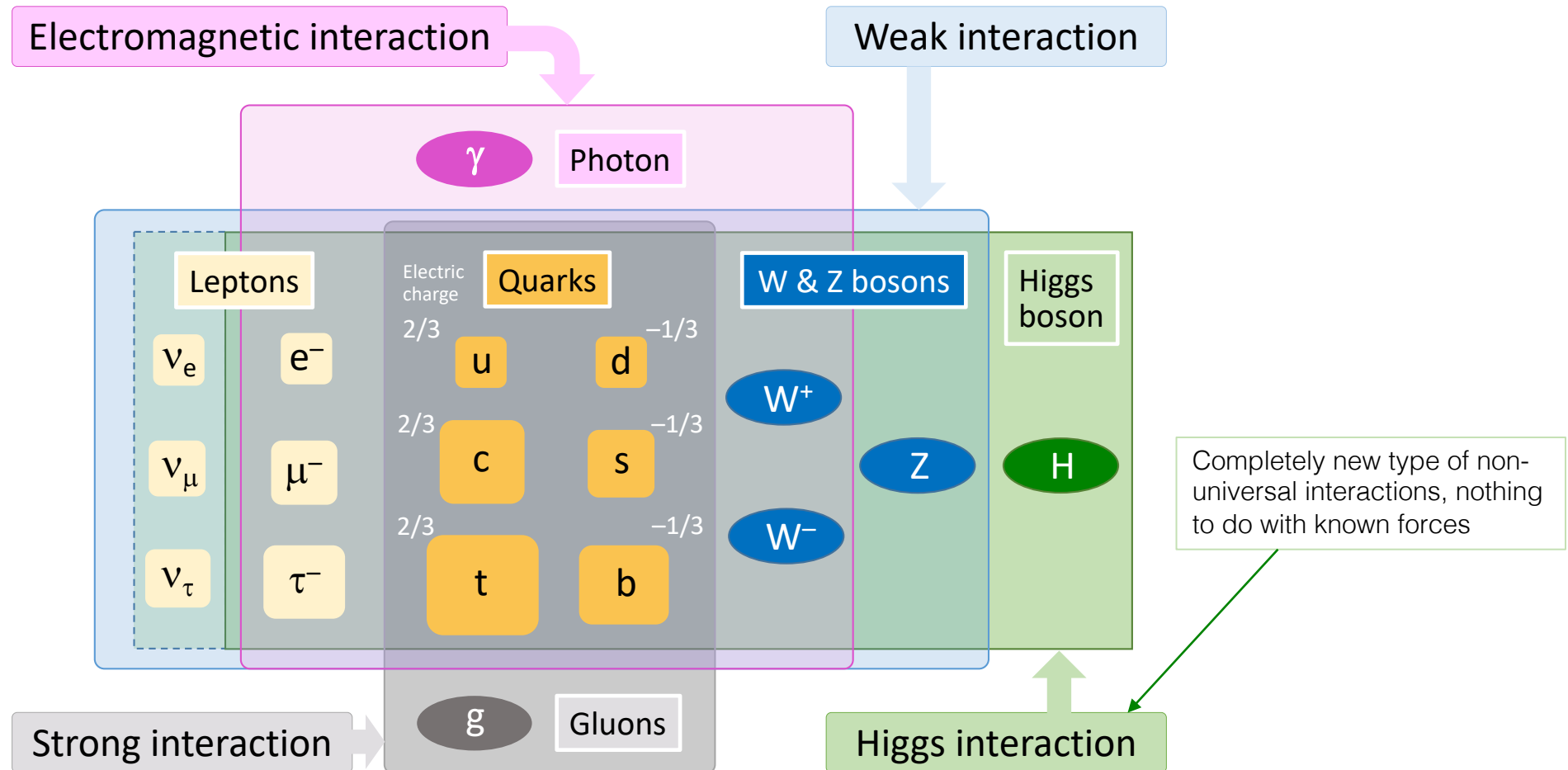
*Philosophiæ Naturalis Principia Mathematica*, published in 1687

**Democritus** relied on phenomenology, since the scientific revolution physicists rely on observation and mathematics to study and describe the physical laws



# The Standard Model

These equations describe all known particles and their interactions





# The Standard Model

As well as larger  
scales of the universe



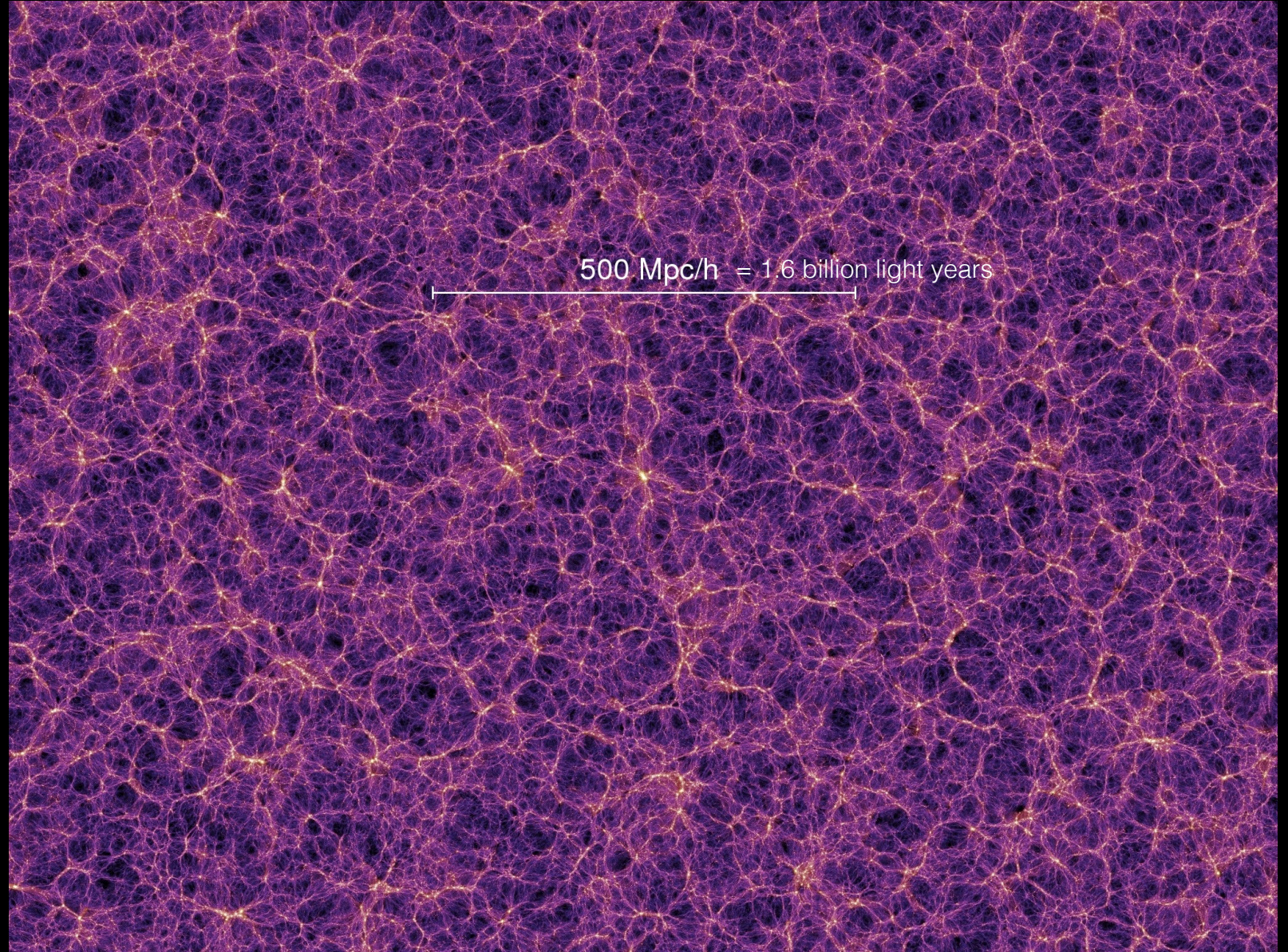
Size of about 220 thousand light years, about 1 trillion stars

Andromeda Galaxy  
(2.5 million light years from Earth)



# The Standard Model

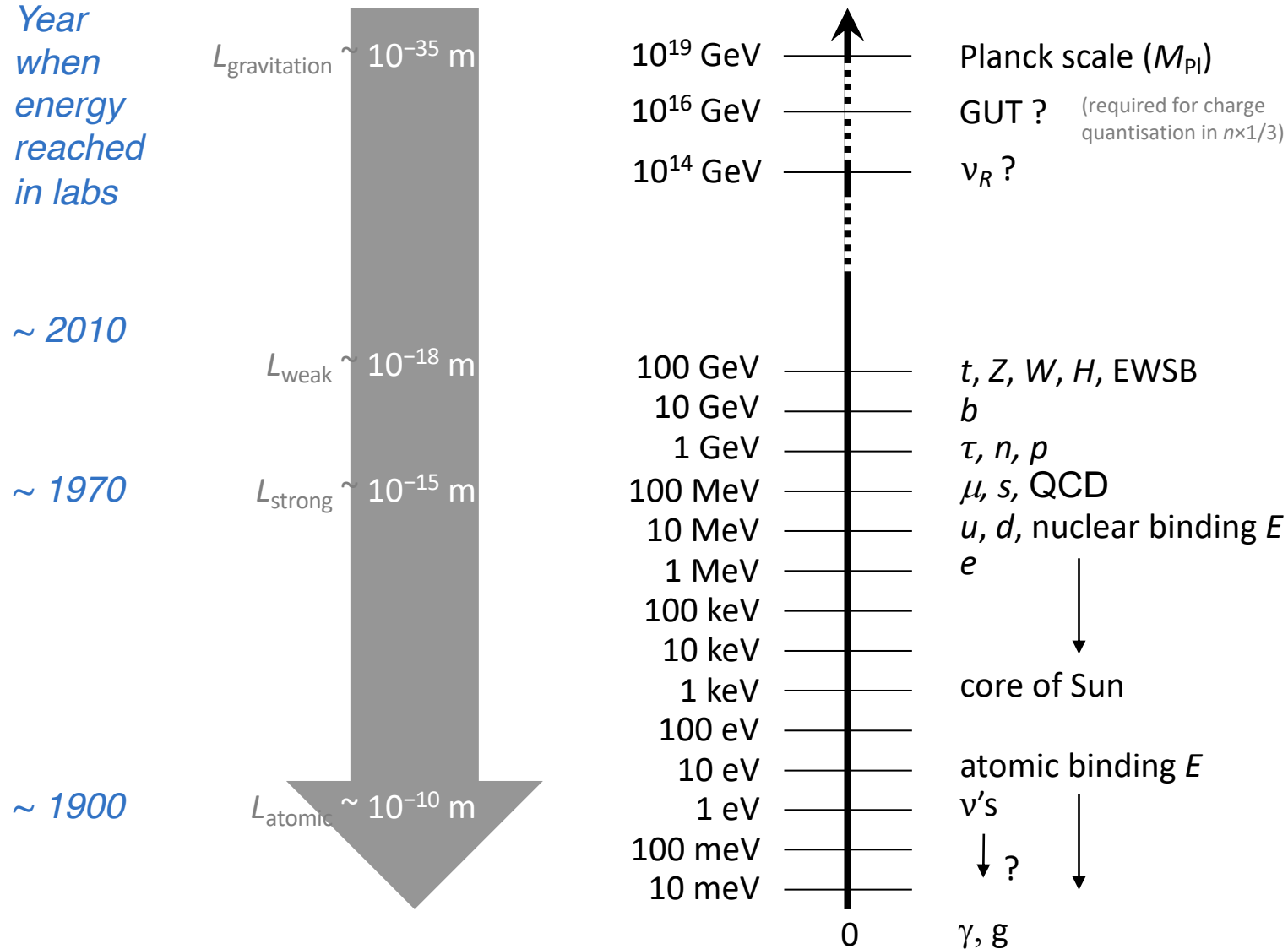
... up to the largest  
scales ...



Simulation of structure formation  
(dark matter, astro-ph/0504097)

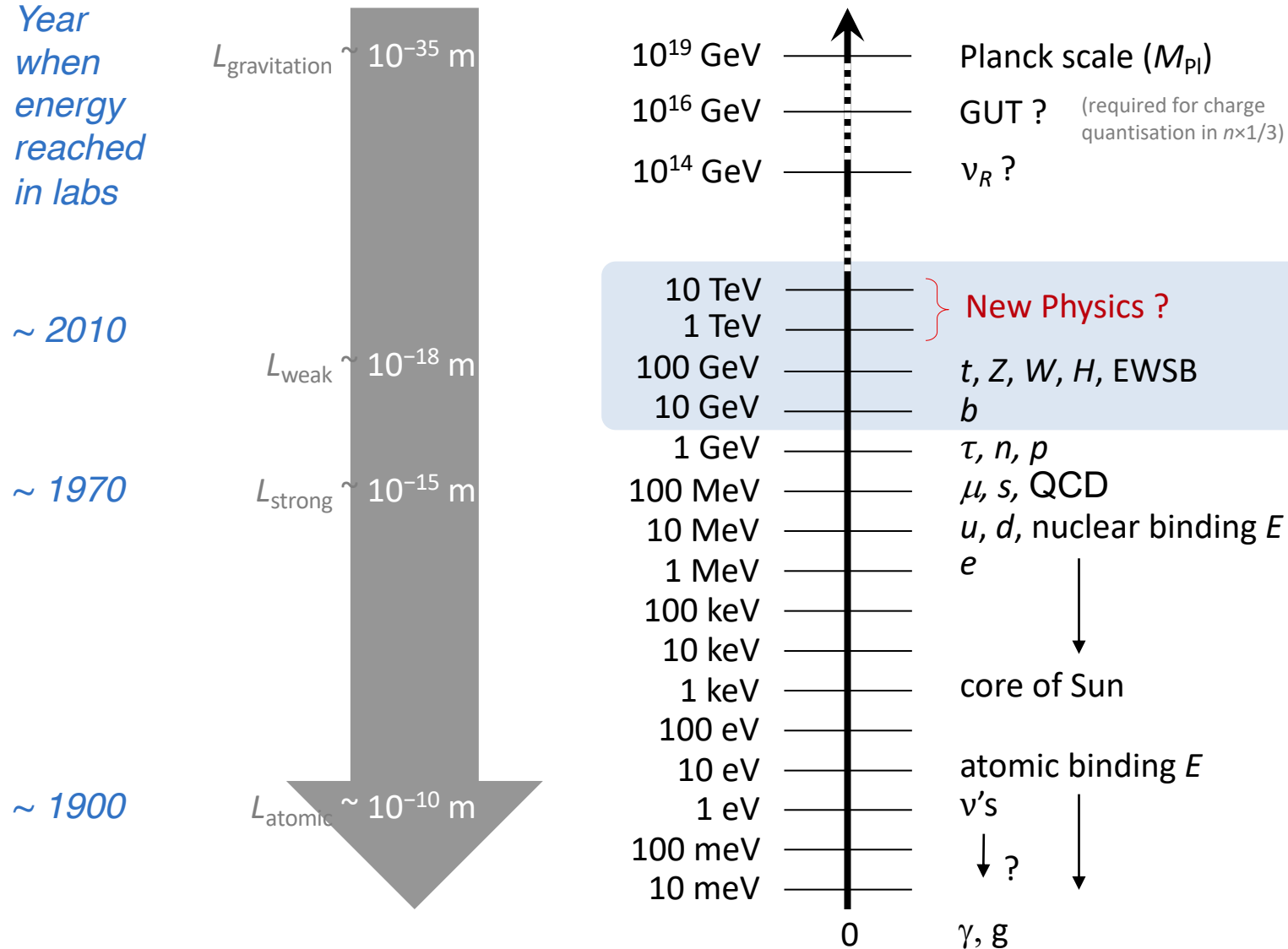


# Mass (= energy) and length scales





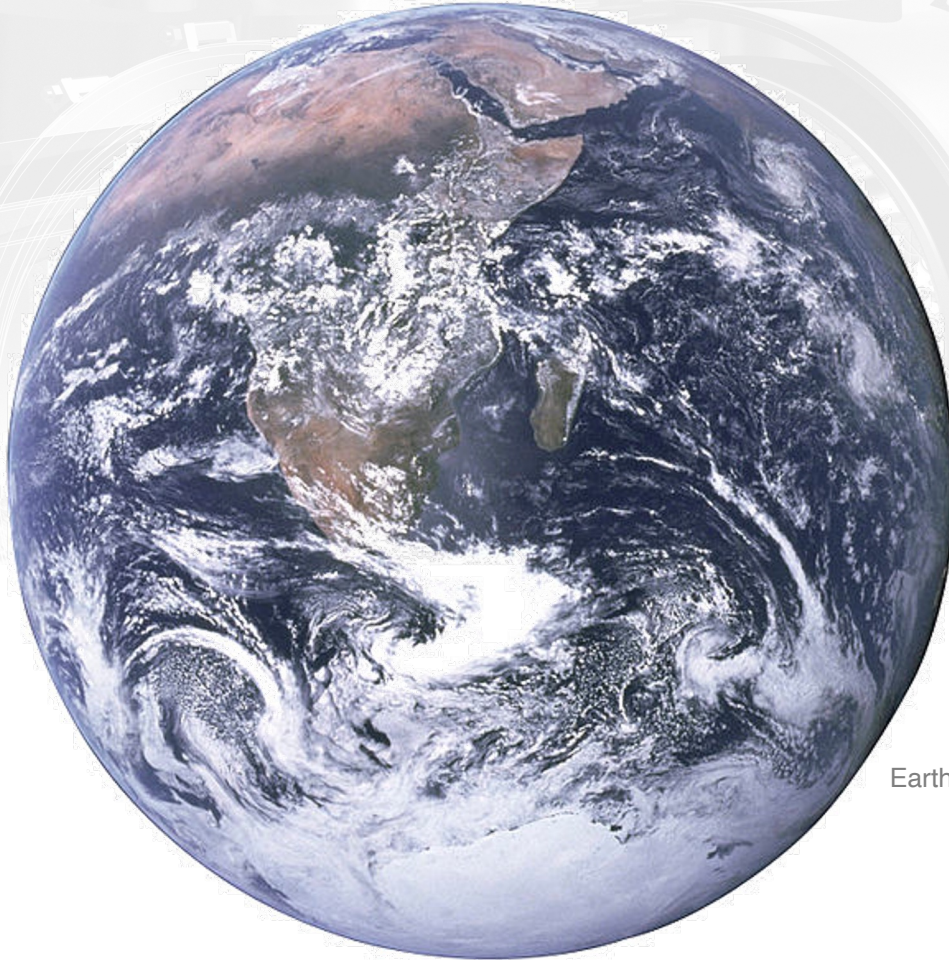
# Mass (= energy) and length scales





*A 1 TeV-frequency microscope looks at really, really tiny objects...*

Nanoscience



Earth

Particle physics today  
(TeV scale)



Siphonaptera (flea)





On 17 May 1954, the first shovel of earth was dug on the Meyrin site in Switzerland under the eyes of Geneva officials and members of CERN staff



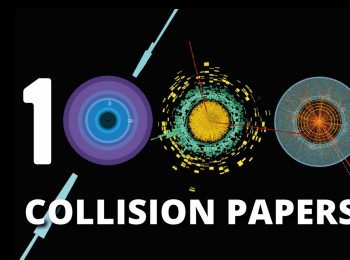
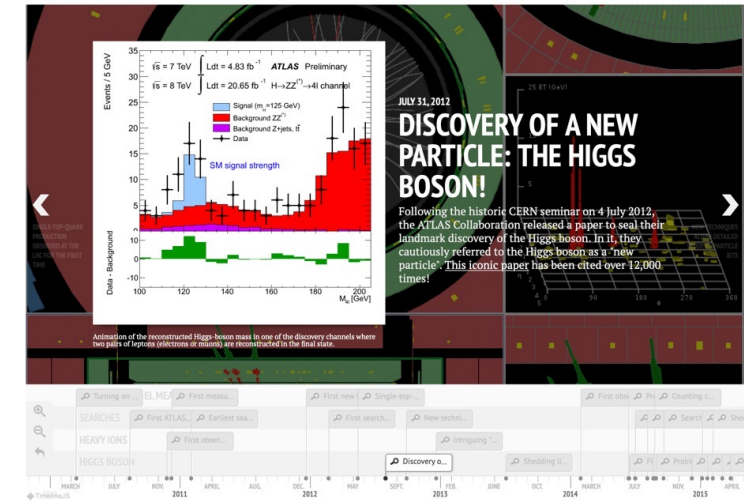
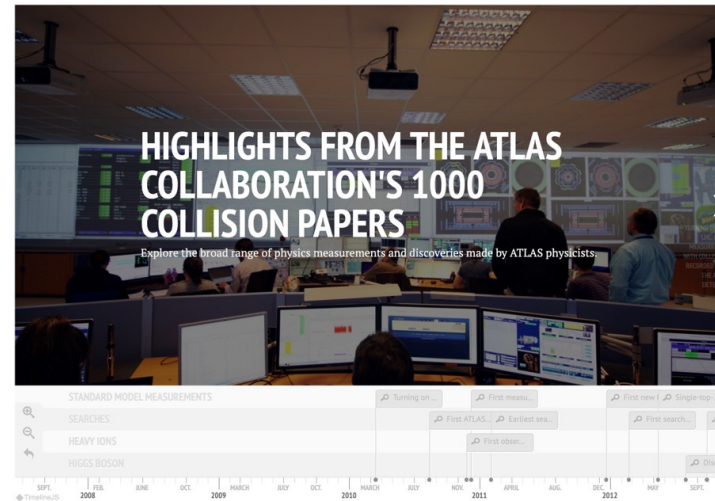
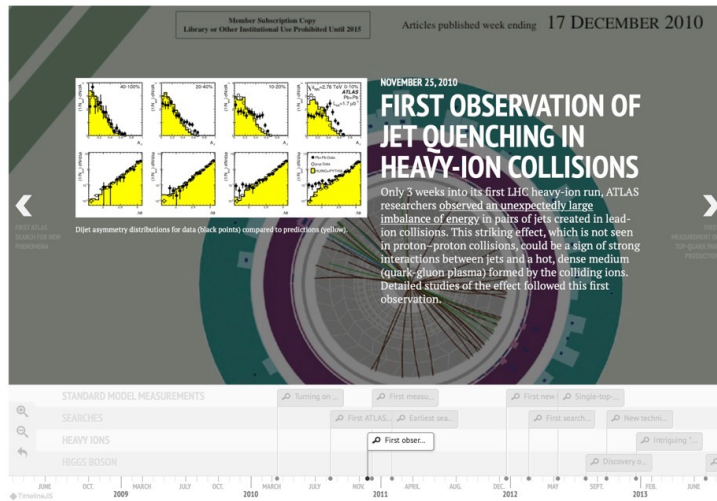
Aerial view of the 25 GeV Proton Synchrotron at CERN in 1965



# This spring we celebrated the results of 1000 collision papers

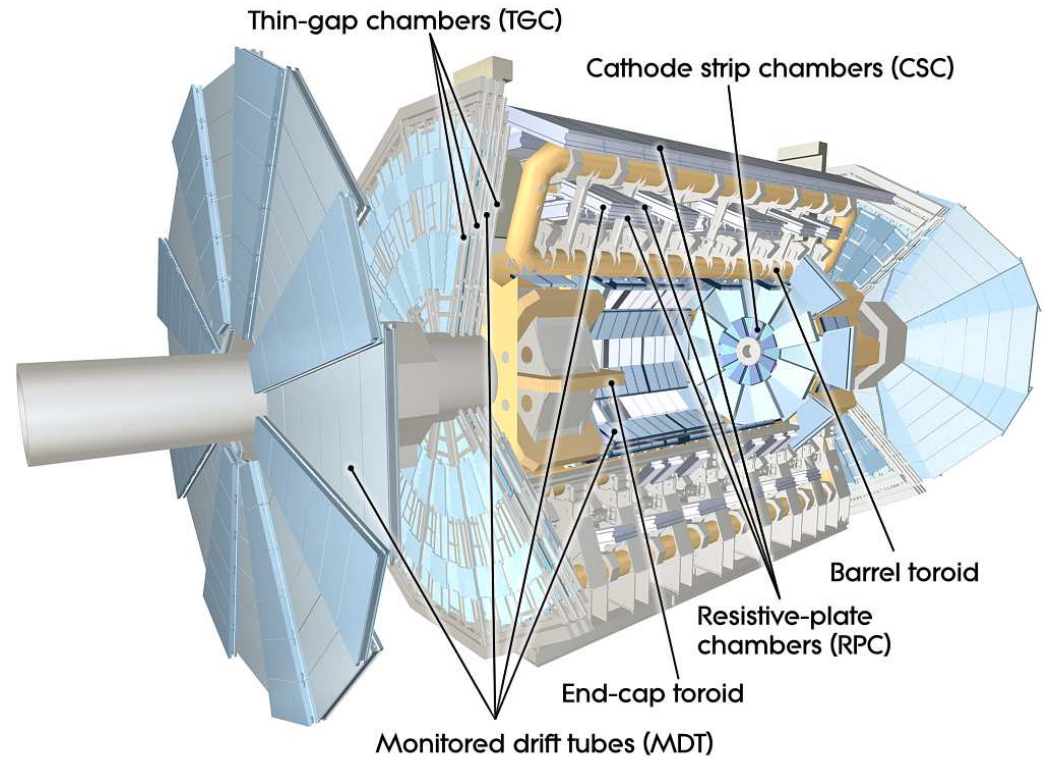
This milestone emphasises the wealth, scientific breadth and impact of our research and publications: the LHC is itself a scientific diversity programme !

- Enjoy a timeline featuring 60 paper highlights: <https://atlas.cern/updates/news/1000-collision-papers>





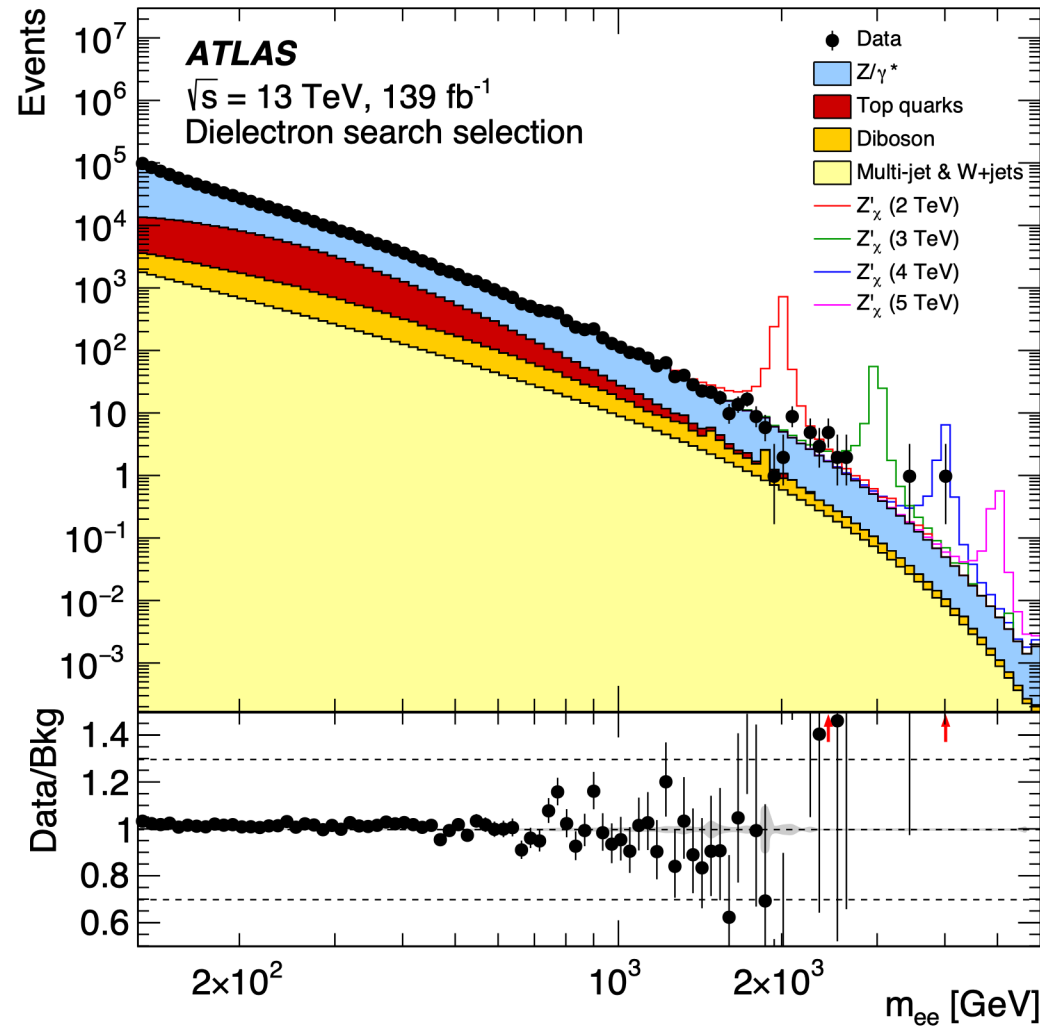
# ATLAS Detector construction and installation – Muons



View on the Big Wheels, intermediate muon stations with four 25 m diameter wheels on each forward side

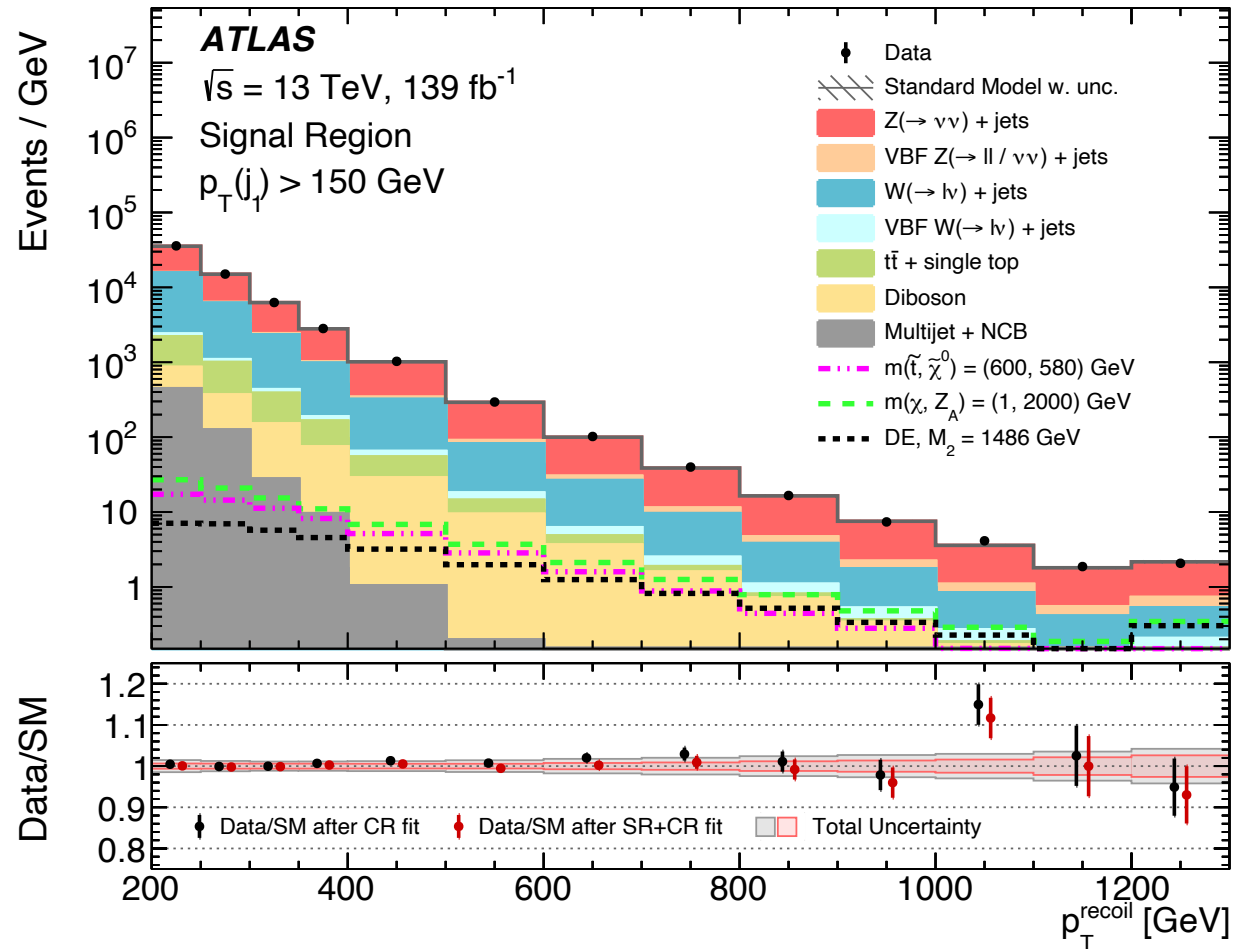


# Do new forces with new carriers exist?





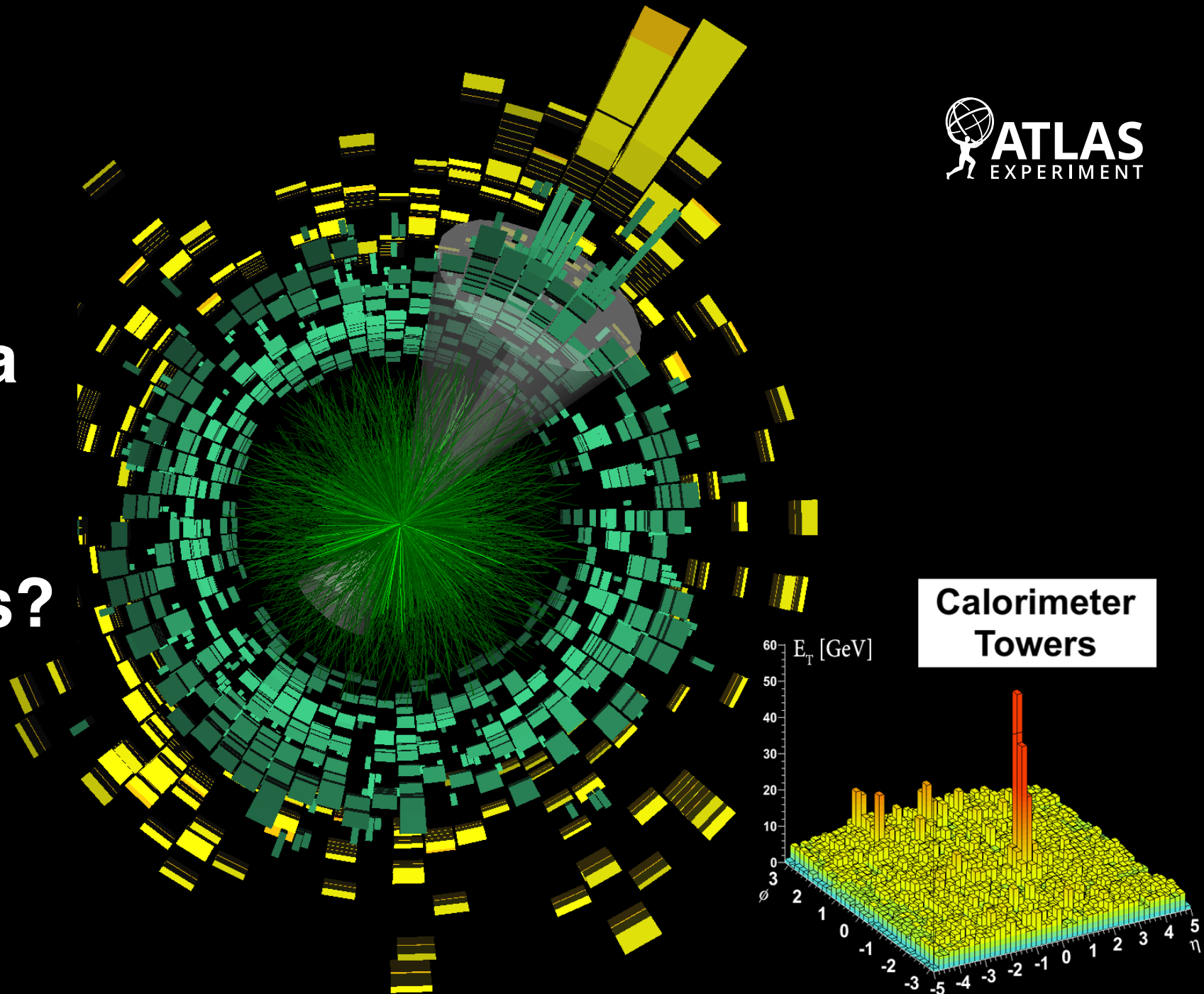
# Are dark matter particles produced at the LHC ?





# What are the properties of the quark-gluon plasma created in the collision of heavy ions?

In collisions of heavy ions, the LHC creates for a very brief moment a quark-gluon plasma of up to 6 trillion degrees, almost half a million times hotter than the core of the sun





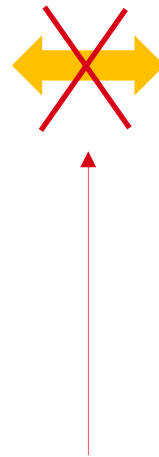
# We have two beautiful, extremely precise theories

## The Standard Model of electromagnetic, weak, strong and Higgs interactions

Predicting, e.g., the magnetic moment of the electron to a relative precision of better than  $10^{-9}$  in agreement with experiment

## General relativity — theory of gravitation

Tested up to an accuracy of order  $10^{-5}$  (Cassini probe [B Bertotti et al., Nature 425, 2003])



**Unfortunately, the SM and general relativity do not work in regimes where both are important (ie, at very small scales)**



# Many questions remain, of which many can be tackled at the LHC

## Scalar sector

- Single doublet or more
- Elementary or composite
- Form of potential
- Origin of Yukawa couplings

## Dark matter

- Composition: WIMP, axions, sterile neutrinos, hidden sector particles, gravitational effect only
- Single or multiple sources

## Expansion of Universe

- Primordial expansion via inflation; which fields, role of quantum gravity?
- Accelerated expansion today: cosmological constant problem

## Strong CP problem

## Quarks and leptons

- Origin of families, mass, mixing, CPV
- Matter–antimatter asymmetry
- Baryon and lepton number conservation (proton decay)

## Neutrinos

- Origin and values of neutrino masses
- Nature: Majorana or Dirac
- CP violation
- Sterile neutrinos

## High-scale physics

- Hierarchy problem and new physics at TeV scale
- Grand unification of forces
- Unification with gravity
- Quantum gravity, string theory



# Preparations for the High-Luminosity LHC





# Preparations for the High-Luminosity LHC





# Scientific priorities for the future

## Implementation of the recommendations of the 2020 Update of the European Strategy for Particle Physics:

- Fully exploit the HL-LHC
- Build a Higgs factory to further understand this unique particle
- Investigate the technical and financial feasibility of a future energy-frontier  $\sim 100$  km collider at CERN
- Ramp up relevant R&D
- Continue supporting other projects around the world

